Part 2: Stars

- Thursday, February 9 — Reading: Chapter 6 [Ed. 9, 10, 11, 12]
  - The nature of light: How we use spectra to measure the properties of stars
- Tuesday, February 14 — Reading: Chapters 8, 9.1, 9.5 or Orion Nebula
  - Stars: distance, luminosity, mass, composition. Star formation. HW2 assnd
- Thursday, February 16 — Reading: Chapter 7.1 — 7.2 or 7.3 on the Sun
  - Stars: Our Sun.
- Tuesday, February 21 — Reading: Chapters 7 or 9 on fusion, 9.2 — 9.5
  - Stars: Stellar models, energy generation, main sequence life
- Thursday, February 23 — Reading: Chapters 10.1 — 10.3
  - Stars: Evolution from main sequence to white dwarf or Type II supernova
- Tuesday, February 28 — Reading: Chapters 10.4, 11 HW 2 due
  - Stars: Type I supernovae; white dwarf stars, neutron stars, black holes
- Wednesday, March 1 — Help session from 4 — 6 PM in Welch 3.502
- Thursday, March 2 — Exam 2 (Part 2)
- Monday, March 6 — Help session from 4 — 6 PM in RLM 4.102
- Tuesday, March 7 — Exam 3 (Parts 1 + 2)
- Thursday, March 9 — Exam 4 (Parts 1 + 2)

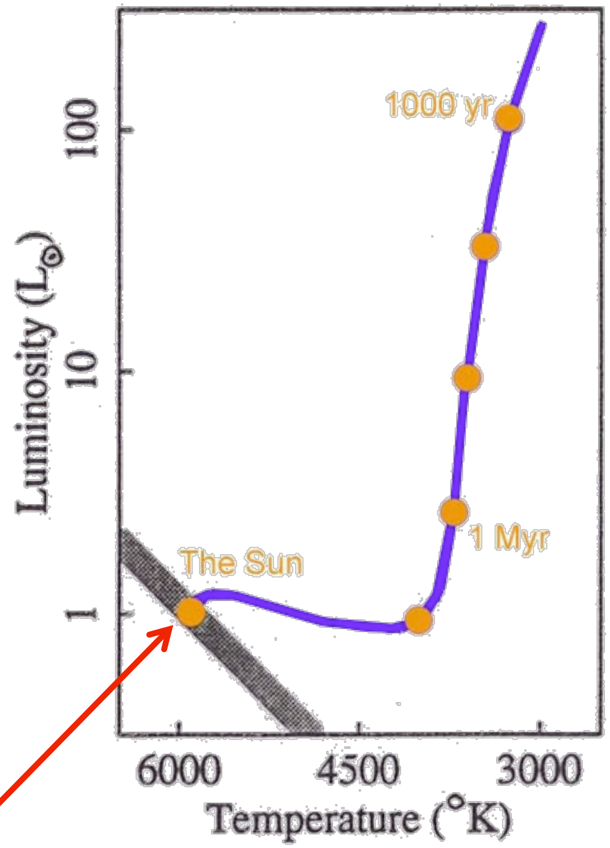
The Sun has been stable for 4 billion years.

Life on Earth has flourished because
the Sun has been stable for over 4 billion years.

Consider:
A change in Earth's mean temperature of only a few tens of degrees
would result in
a global iceball or a hot desert.

Why
stars on the Main Sequence are so stable
is a major subject of this lecture.

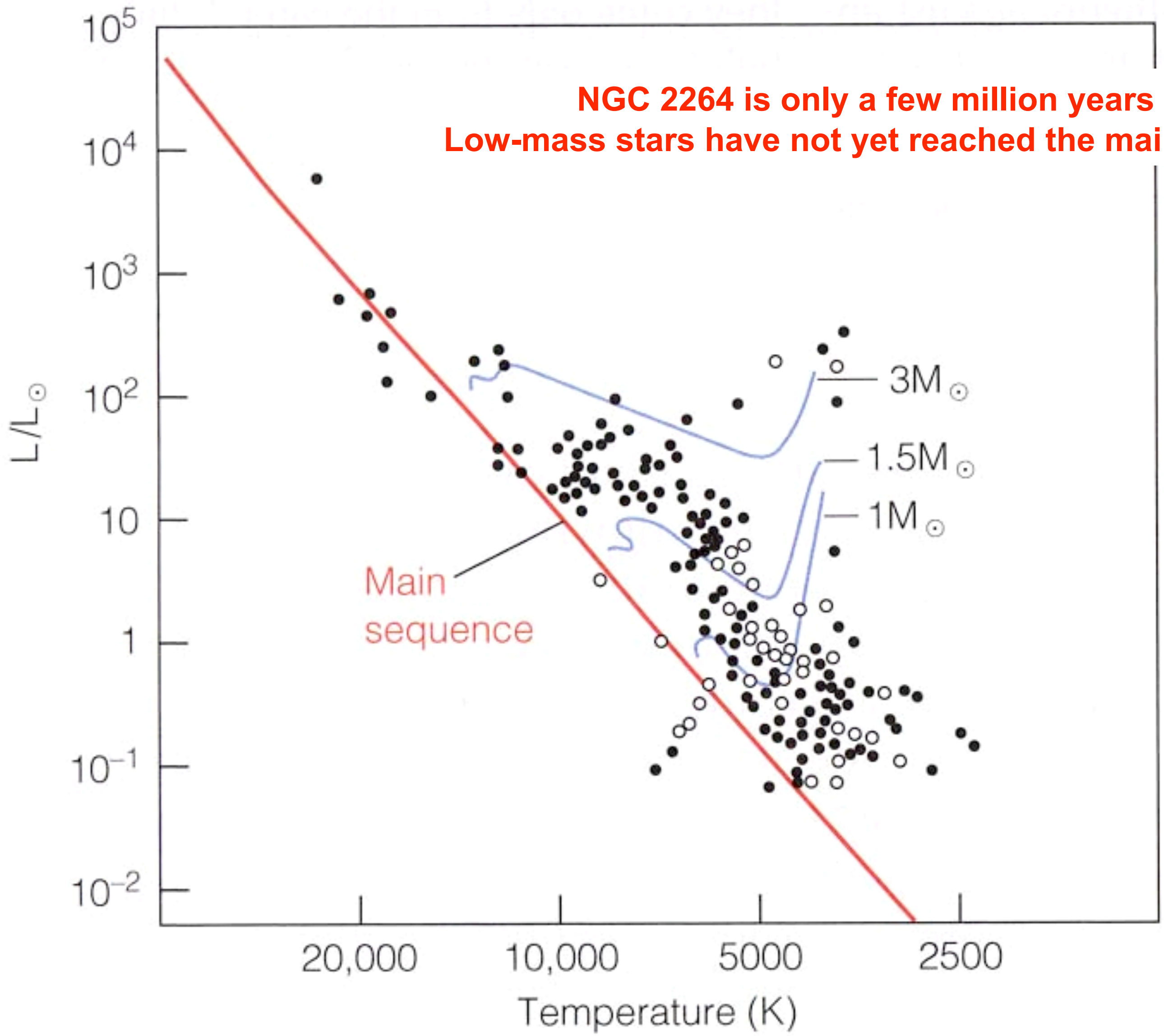
Pre-Main-Sequence Evolution



As a protostar shrinks and gets hotter, the central temperature of the star eventually gets high enough for nuclear reactions that convert hydrogen to helium. The energy released keeps the interior temperature constant with no need for further contraction. The star settles onto the main sequence.

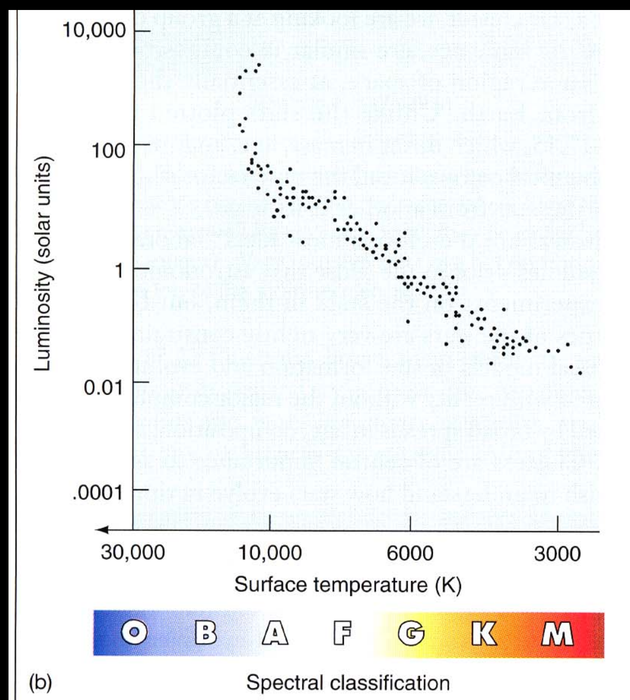
Star Cluster NGC 2264

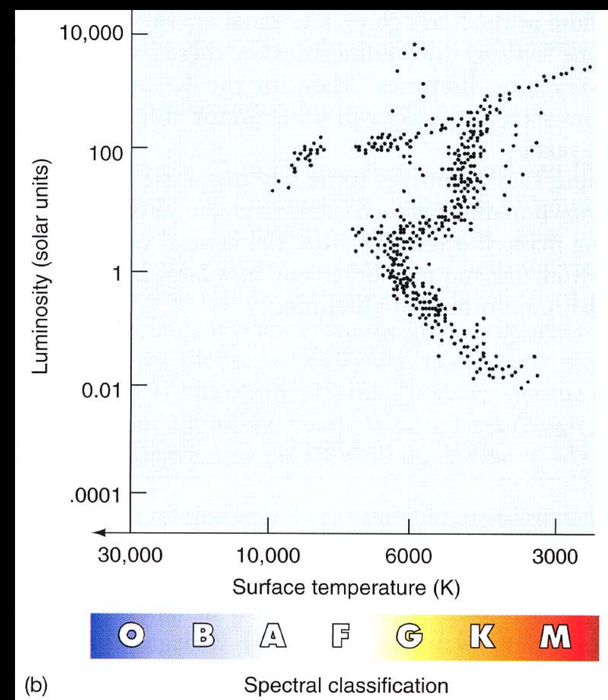
NGC 2264 is only a few million years old.
Low-mass stars have not yet reached the main sequence.



The Pleiades are about 10^8 years old.
All stars have reached the main sequence.
The most massive stars have left the main sequence.

The globular cluster Omega Cen
is ~ 13×10^9 years old.
Many stars have left the main sequence..





naked eye can see only its brightest stars. (b) The stars of this well-known open cluster yield an H–R diagram.

diameter. (b) An H–R diagram for many (but not all) of its star

Main Sequence Structure

Main sequence stars produce energy by fusing hydrogen into helium in their centers.

The radius, temperature, luminosity, and lifetime of a main sequence star are determined by its mass.

Pressure balance

A star is an immense ball of gas. The pressure at any point is equal to the total weight of the gas above it. Because a star is so massive, the gas inside it is very compressed and very hot. The central temperature of a star like the Sun is about 15 million K ≈ 27 million degrees F.

Energy Generation

At such temperatures, nuclei collide fast enough to undergo nuclear reactions that release energy. **All main sequence stars contain a core in which hydrogen is being converted into helium. This is what makes a star a main sequence star.**

Energy Transport

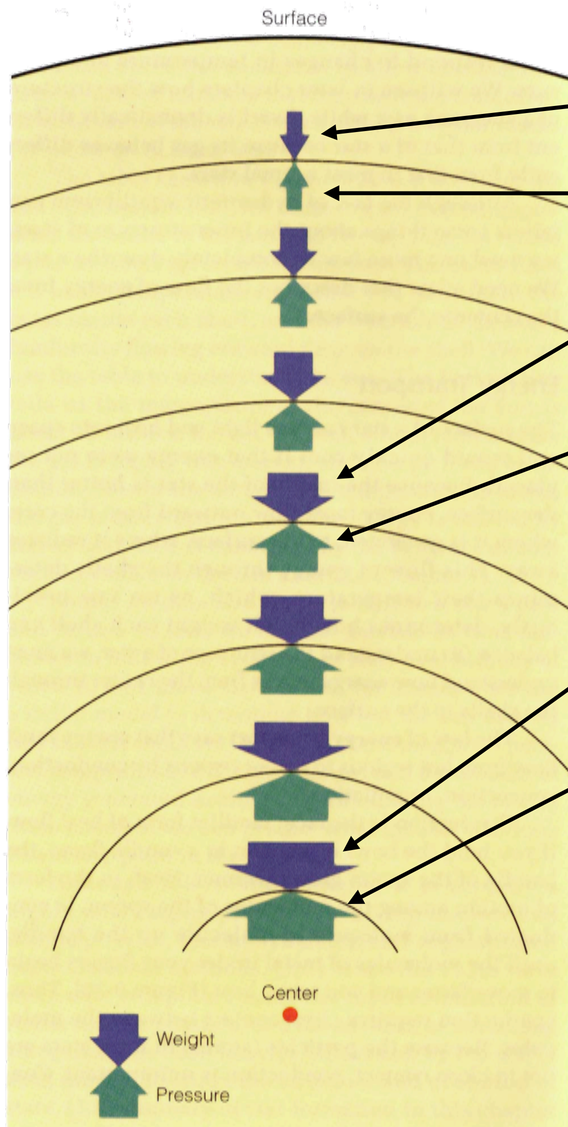
Energy generated by nuclear reactions constantly escapes from the star. This happens by radiation or by convection — whichever process carries energy the fastest given the conditions inside the star is the one that controls energy transport.

Pressure Balance

Pressure balance

The pressure at any point is equal to the total weight of the gas above it.

Because a star is so massive, the gas inside it is highly compressed and gets very hot.



Near the surface, the weight of gas above you is not very large and the pressure is low.

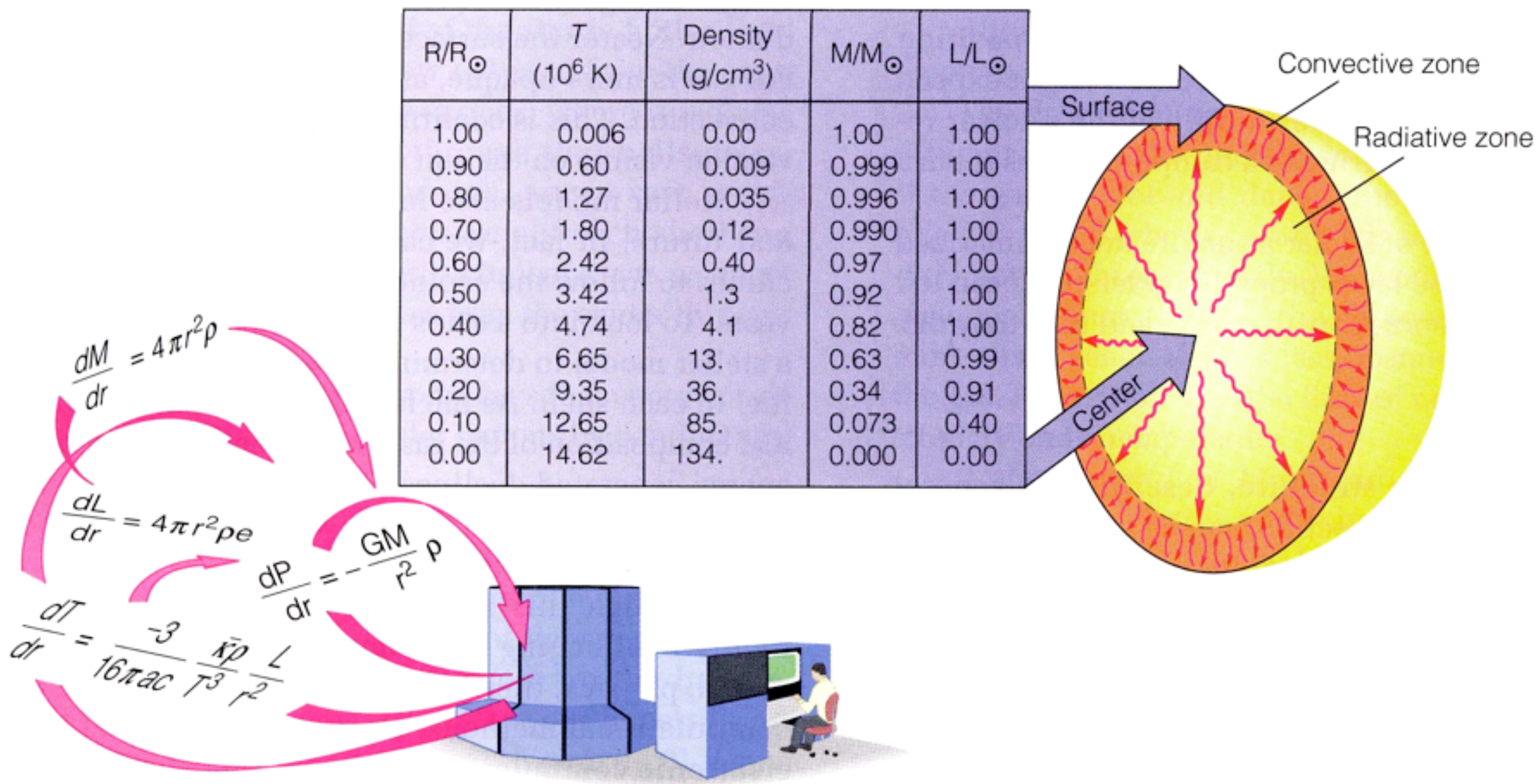
Farther into the star, there is more gas above you; the weight of this gas is bigger, so the pressure has to be bigger than near the surface.

Near the center, the whole weight of the star is above you and so the pressure has to be enormous to hold up the star.

High pressure is made by high temperature — by collisions of particles that move at high speeds. So it must be very hot near the center and cooler farther out.

Calculating the Internal Structure of a Star

The equations that govern pressure balance, energy generation and energy transport can be used to calculate the interior structure of a star from its surface properties.



$R/R_\odot$	T (10^6 K)	Density (g/cm^3)	$M/M_\odot$	$L/L_\odot$
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.27	0.035	0.996	1.00
0.70	1.80	0.12	0.990	1.00
0.60	2.42	0.40	0.97	1.00
0.50	3.42	1.3	0.92	1.00
0.40	4.74	4.1	0.82	1.00
0.30	6.65	13.	0.63	0.99
0.20	9.35	36.	0.34	0.91
0.10	12.65	85.	0.073	0.40
0.00	14.62	134.	0.000	0.00

Figure 9-22
A stellar model is a table of numbers that represents conditions inside a star. Such tables can be computed using the four laws of stellar structure, shown here in mathematical form. The table in this figure describes the sun. *(Illustration design by author)*

Stability Provides A Powerful Thermostat

A main sequence star is stable.
It adjusts to any disturbance
so as to maintain a nearly constant radius, temperature and absolute luminosity.

Suppose the star contracts a little. Then its center gets hotter. But the proton—proton cycle's energy output is proportional to temperature^{5}. The CNO cycle's energy output is proportional to temperature$^{(15 \text{ to } 20)}$. Therefore much more energy is generated. So the temperature rises. But this increases the pressure. So now the pressure is too big for the weight of the gas above it. Therefore the star expands and cools off again. This reduces the nuclear reaction rate back to what is needed to keep the star in equilibrium.

If too little energy is generated, the star contracts, heats up, and increases its energy generation.

So a star is wonderfully well thermostated.
This keeps its energy output nearly constant.

This is why the Sun has been so stable for 4.5 billion years.
This is why life on Earth is possible.

Stability Provides A Powerful Thermostat

A main sequence star is stable.

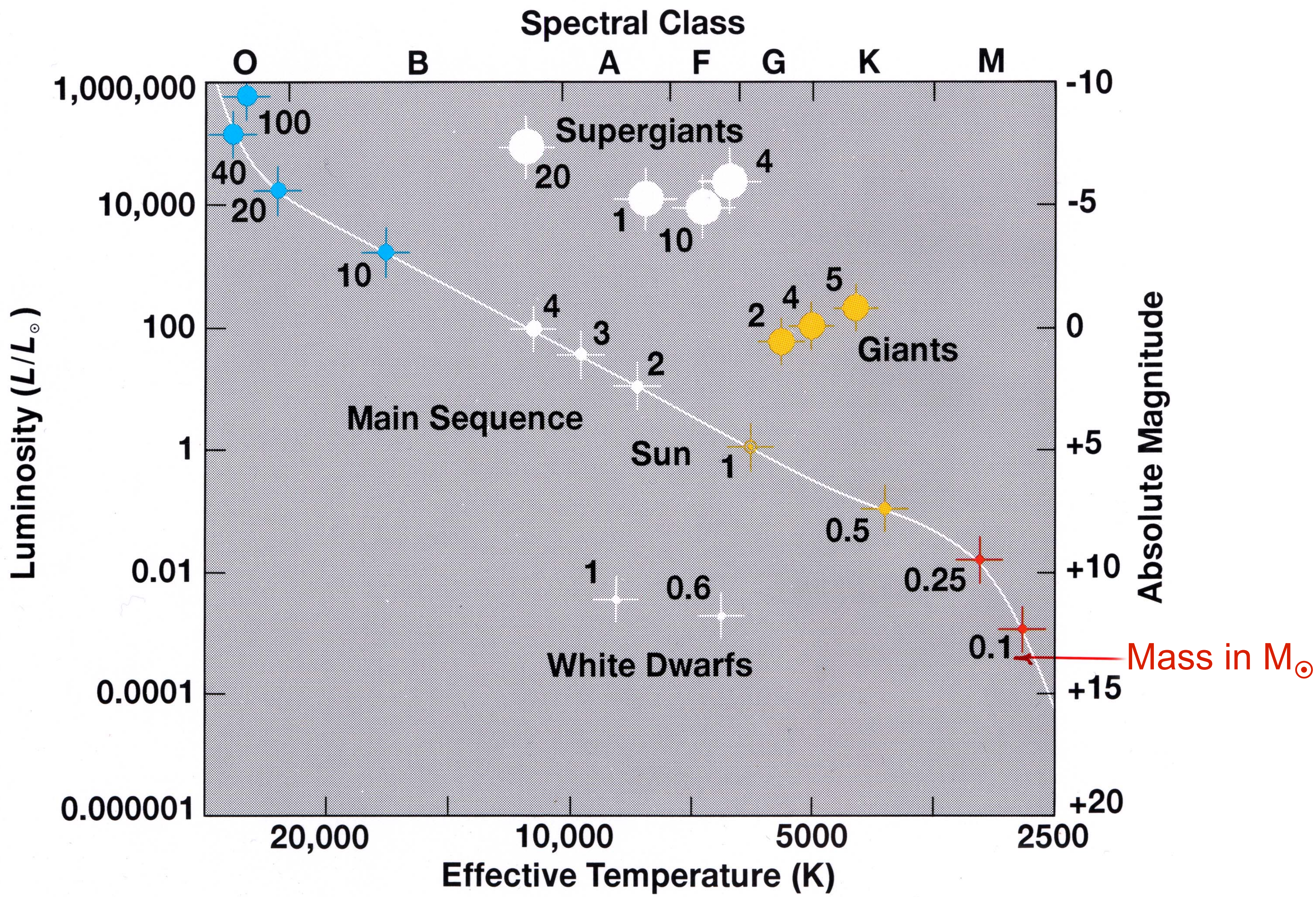
It adjusts to any disturbance so as to maintain a nearly constant radius, temperature and absolute luminosity.

Mass Governs All

The balance between gravity and pressure, between energy generation and energy transport — everything that determines the structure of a main sequence star — depends on the star's mass. All main sequence stars that have the same mass and composition have the same radius, temperature, and luminosity. Since most stars have similar composition, all main sequence stars of a given mass are close together in the HR diagram.

This explains why the main sequence is a thin, nearly linear feature in an HR diagram. Stars of all masses are constantly forming in the Milky Way. These stars spend most of their lives on the main sequence. When plotted together, these stars form a line in an HR diagram.

Review: Masses on the Main Sequence



What Powers Stars?

Gravitational energy? While stars and planets are forming, they contract. Every particle is getting closer to every other particle. So the gravitational attraction between all of the particles is getting stronger. Heat is generated as the protostar contracts and the pressure rises: the star is converting gravitational energy into heat. But this energy source is too weak to power stars for long. **If gravity were the only energy source for stars, they would shine for only ~ 30 million years**.

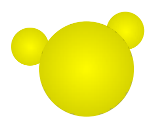
Chemical reactions also generate energy. They also are too weak to power stars for long. They would power the Sun for less than 50,000 years.

Nuclear reactions are the only known energy source that can power stars at the luminosities that we observe for more than 10^{10} years.

Chemical and Nuclear Reactions

In a **chemical reaction**, atoms stick together and form compounds because they share electrons. That is, the atomic nuclei remain separate, but the electron clouds surrounding the nuclei stick together, so the atoms are glued together.

An example of a compound is water, H_20.



In a **nuclear reaction**, **nuclei stick together and make different nuclei.**

In both types of reactions, simple ingredients can combine to make more complicated products or complicated ingredients can break up into simpler products. Both types of reactions either require energy to make them happen or release excess energy.

Nuclear reactions are much more energetic than chemical reactions.

Two Kinds of Nuclear Reactions

In **<u>nuclear fusion</u>**, light nuclei collide, stick together, and form a heavier nucleus. This happens only if the attractive **strong nuclear force** overcomes the repulsive **electromagnetic force** that pushes protons apart. Then the new nucleus is more stable ("more tightly held together") than the collection of ingredients from which it was made. Therefore energy is released. Nuclear fusion reactions power stars. They also power hydrogen bombs.

In **<u>nuclear fission</u>**, an unstable heavy nucleus spontaneously breaks up into more stable light nuclei. The reaction usually releases a few byproduct particles. Since the product nuclei are more stable than the original nucleus, fission also produces excess energy. Nuclear fission powers atomic bombs. It does not power stars, but it does power the expansion of some supernova explosions.

NOTE

Light nuclei are less stable than moderately massive nuclei,
so fusion releases energy.

Very massive nuclei are less stable than moderately massive nuclei,
so fission releases energy, too.

Why?

Protons all have positive electric charge, so they repel each other electromagnetically.

But they attract each other by the strong nuclear force.

The strong nuclear force works only over very short distances.

Small nuclei are smaller than the range of the strong nuclear force. If you add a particle, it attracts all the others by the strong nuclear force. They attract it. The nucleus is held together more tightly than before the new particle was added.

The most massive nuclei are bigger than the range of the strong nuclear force. Now if you add a particle, the nucleus gets still bigger, and all the particles in it attract each other a lot less. But the electromagnetic repulsion is long-range, so the protons repel each other only a little less. If you added particle a proton, it is especially destabilizing. The result is that the nucleus gets less stable when you add a particle (either a proton or a neutron).

The Most Stable Nucleus Is Iron

It is energetically favorable
to combine very light nuclei into heavier ones
and
to split very heavy nuclei into lighter ones.

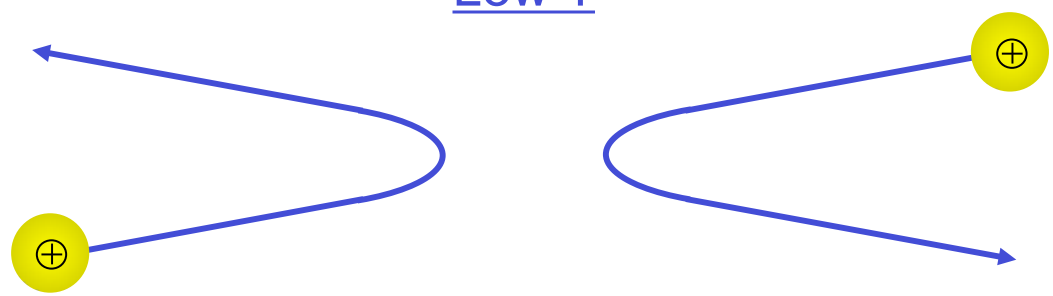
So there must be a most stable nucleus,
and it must be intermediate in mass.

The most stable nucleus is iron.

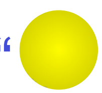
Nuclear Fusion Requires High Temperatures

Higher T ⇔ particles are moving faster

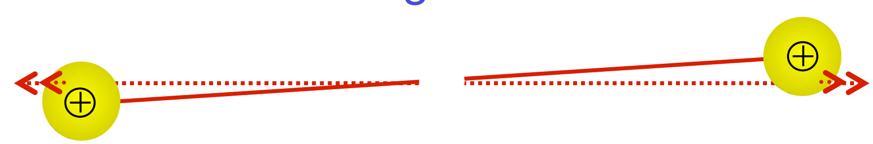
Low T



Protons repel and bounce off each other because they never get closer together than the range

“  ”

of the strong nuclear force.



High T

At high temperatures, protons move much faster, so despite the repulsion, they get closer together than the range of the strong force. As a result, the attraction of the strong force wins out over electromagnetic repulsion and the protons fuse together.

Conservation of Energy

One of the most fundamental laws of nature is:

Energy is never created or destroyed.

However, it can be converted from one form to another.

Matter is "Frozen Energy"

Albert Einstein realized that matter and energy are equivalent — either can be converted into the other. The energy in a mass **m** is given by:

$$\boxed{E = mc^2}$$

Mass — Energy

Energy can be produced by combining things that attract each other or by separating things that repel each other. The total mass of the stuff producing the energy decreases when the energy is released. The mass lost **m** is related to the energy emitted by $\mathbf{E = mc^2}$.

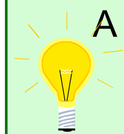
Chemical Energy

Chemical reactions extract energy from electrical forces. The simplest chemical reaction is the recombination of an electron and a proton:

$$e + p \Rightarrow H + 13.6 \text{ eV}.$$

About 0.0000015 % of the mass is converted to energy.

An electron Volt, is a unit of energy.
1 eV = 1.6×10^{-19} joules



A 100 watt light bulb emits
100 j / s or
6.3×10^{20} eV / s.

Nuclear Energy

Nuclear forces yield much more energy than electrical forces.
An example is the fusion of two nuclei of heavy hydrogen:

$$^{2}H + {}^{2}H \Rightarrow {}^{3}He + p + 4 \text{ million eV}.$$

About 0.11 % of the mass is converted to energy.

Gravitational Energy

Gravitational energy is released whenever gravity brings things together. Up to 10 % of the mass can be converted to energy, but only when black holes are involved.

Fuel For The Sun

The Sun is powered mostly by the proton-proton reaction:

$$6p \Rightarrow {}^4He + 2p + 2e^+ + 2n + 26 \text{ million eV}.$$

This converts 0.7 % of the mass into energy.

How much matter does it take to make the Sun shine?

Each second, the Sun emits 3.8×10^{26} joules of energy. This requires the destruction of

$$m = \frac{E}{c^2} = \frac{3.8 \times 10^{26} \text{ kg m}^2 / \text{ s}^2}{(3.0 \times 10^8 \text{ m / s})^2} = 4.2 \times 10^9 \text{ kg}$$

of matter. This is the mass of a ball of water with a radius of 100 m.

Fusion of hydrogen to helium converts mass to energy with an efficiency of 0.7%.
So the Sun must convert

$$\frac{4.2 \times 10^9 \text{ kg}}{0.007} = 6.0 \times 10^{11} \text{ kg} \approx 660 \text{ million tons}$$

of hydrogen to helium every second. This is the mass of a ball of water with a radius of 500 m.

So far, in 4.5 billion years, the Sun has converted 0.03 % of its mass into energy.

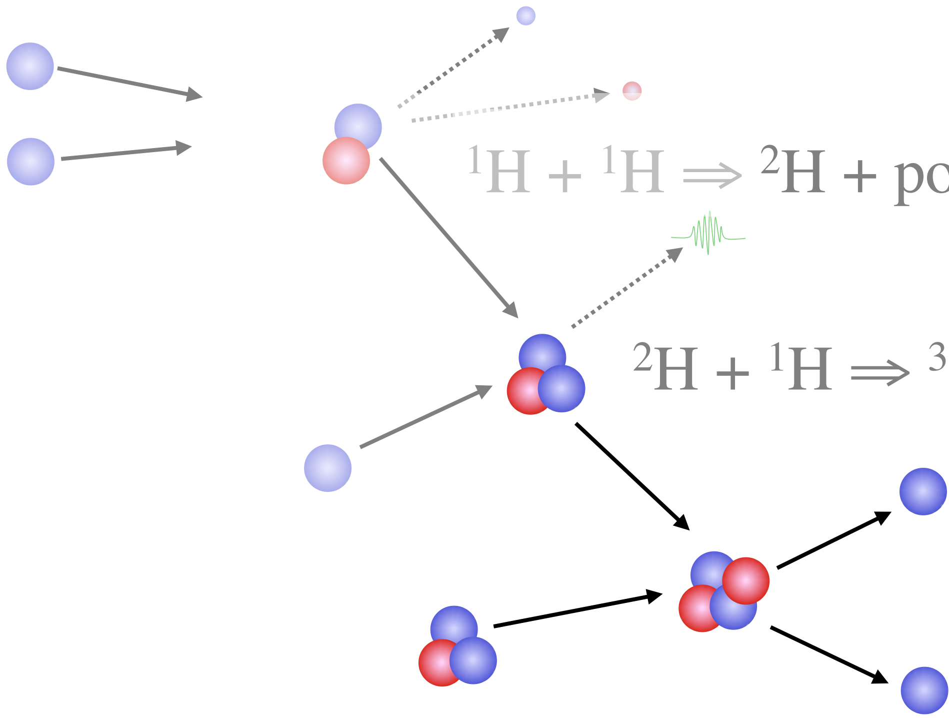
How long will the fuel last?

The mass of the Sun is 2.0×10^{30} kg and 3/4 of it is hydrogen.
If the Sun converted all of its hydrogen to helium at the present rate, it would live for 80×10^{9} years. In practice, this can't happen, because the outer parts of the Sun will never get hot enough.

But it is clear that nuclear reactions can easily power the Sun for a lot longer than its present age of 5×10^{9} years.

In fact, the Sun will live for about 10×10^{9} years.

The Proton - Proton Chain

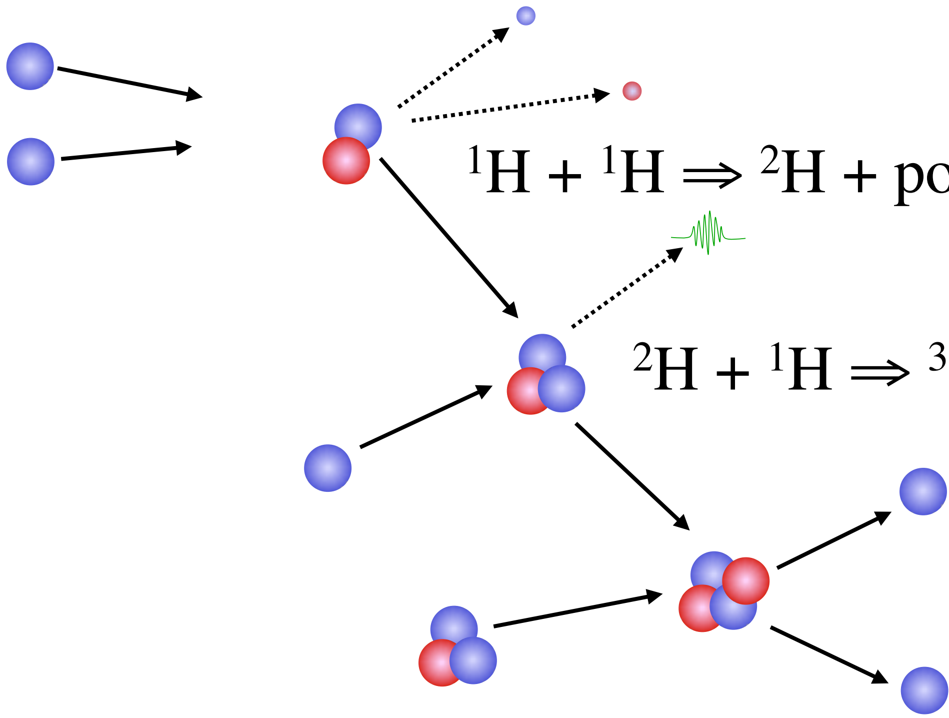


$^{1}H + {}^{1}H \Rightarrow {}^{2}H$ + positron (e^{+}) + neutrino (ν)

$^{2}H + {}^{1}H \Rightarrow {}^{3}He$ + photon

$^{3}He + {}^{3}He \Rightarrow {}^{4}He + {}^{1}H + {}^{1}H$

The Proton - Proton Chain



$^{1}H + {}^{1}H \Rightarrow {}^{2}H$ + positron (e^{+}) + neutrino (ν)

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$^{3}He + {}^{3}He \Rightarrow {}^{4}He + {}^{1}H + {}^{1}H$

Energy produced $\propto$ Temperature^{5}

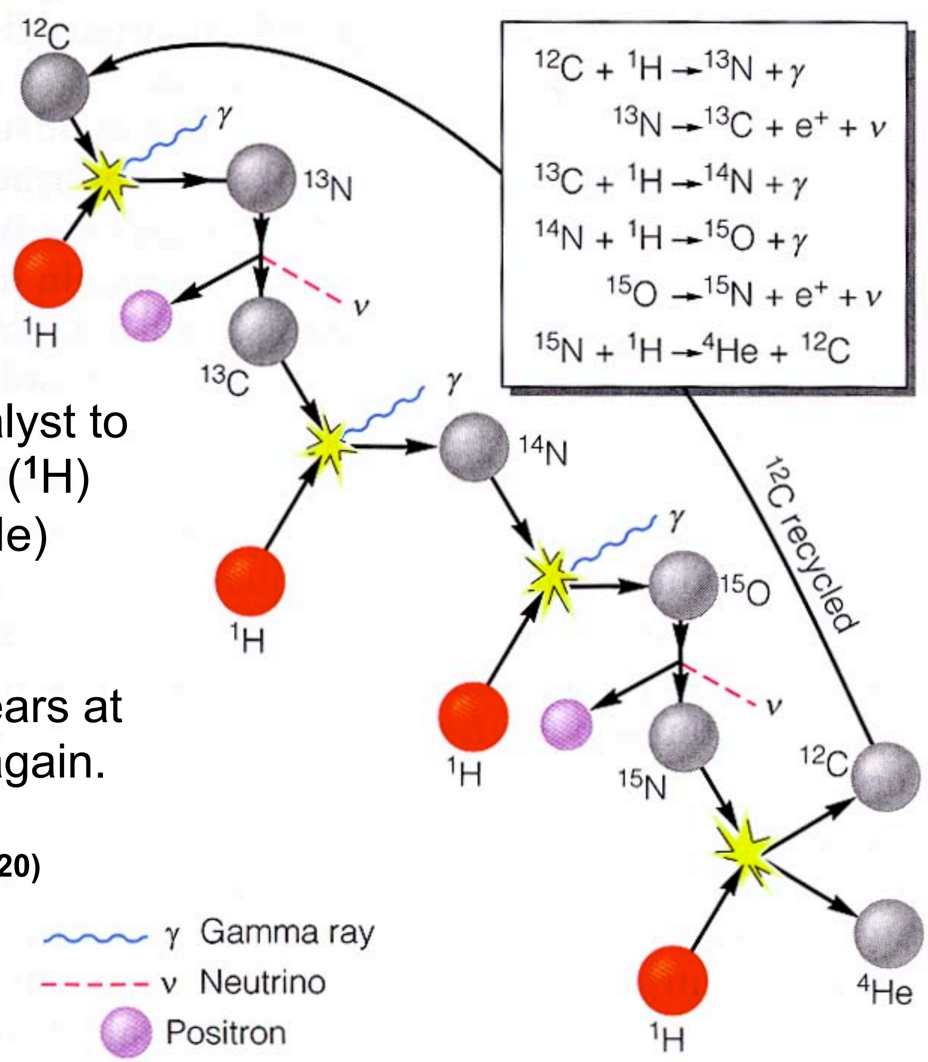
The proton—proton chain dominates if the central temperature is between ~ 7 and ~ 16 million K.

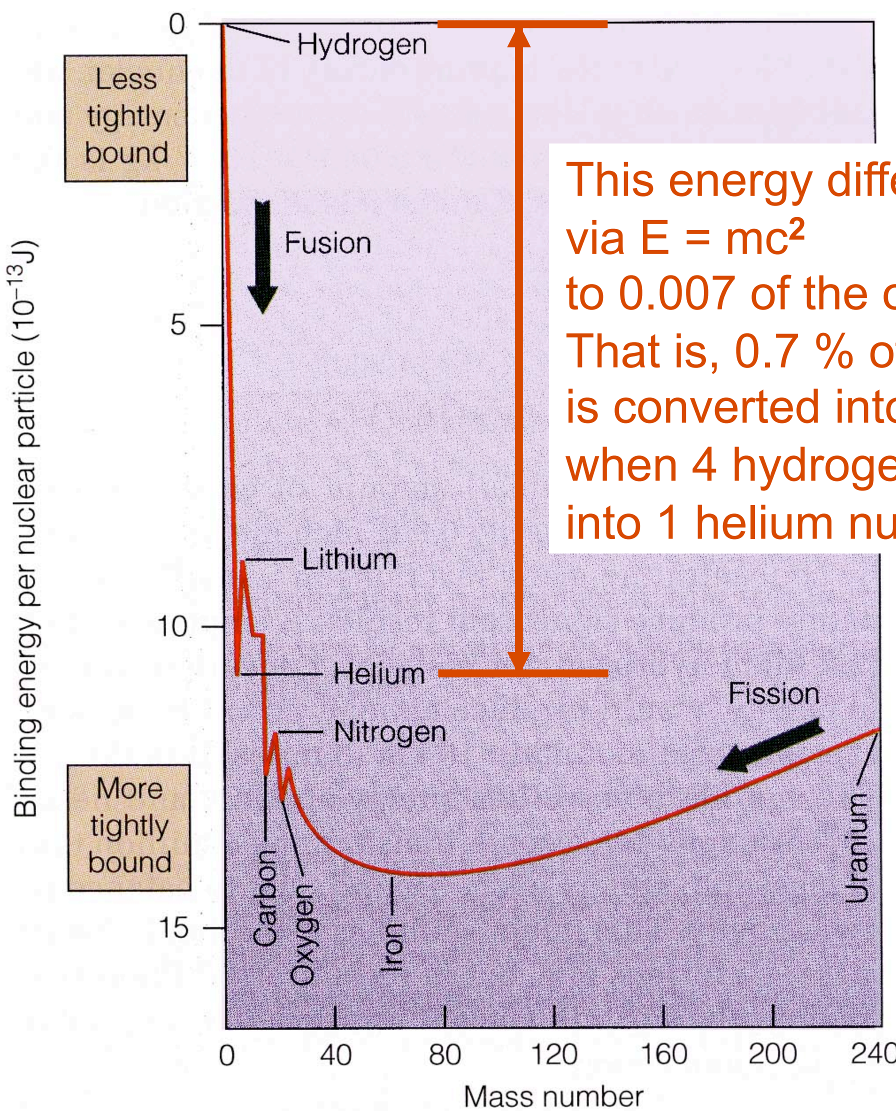
The CNO cycle
dominates if the central temperature > 18 Million K.

The CNO cycle
uses carbon (^{12}C) as a catalyst to combine 4 hydrogen nuclei (^{1}H) into one helium nucleus (^{4}He) plus energy.

The carbon nucleus reappears at the end, ready to be used again.

Energy $\propto$ Temperature$^{(15\text{ to }20)}$





This energy difference corresponds
via $E = mc^2$
to 0.007 of the original mass.
That is, 0.7 % of the original mass
is converted into energy
when 4 hydrogens are converted
into 1 helium nucleus.

The red line in this graph shows the binding energy, the energy that holds an atomic nucleus together, for all the different atoms plotted by their atomic number, the number of protons and neutrons in their nucleus. Both fission and fusion nuclear reactions move downward in the diagram (arrows) toward more tightly bound nuclei. Iron has the most tightly bound nucleus, so no nuclear reactions can begin with iron and release energy.

Notice that 3/4 of the energy that you can get out of converting hydrogen to iron is already extracted by converting hydrogen to helium.

This is why most of a star's life is spent on the main sequence.

The Solar Neutrino Problem

The Sun is powered mostly by the proton—proton reaction:

$$6p \Rightarrow {}^{4}He + 2p + 2e^{+} + 2n + 26 \text{ million eV.}$$

The two neutrinos carry away about 0.5 million eV of energy.

Neutrinos interact extremely weakly with other matter and photons. It would take a slab of lead about 10 ly thick to absorb a typical neutrino. So the Sun and the Earth are transparent to neutrinos. Unlike light, which takes a million years to scatter its way out of the Sun, neutrinos get from the center to the surface in 2 seconds. Eight minutes later, they pass by the Earth. Therefore:

Neutrinos are a window into the solar interior.

About 100 billion neutrinos from the Sun pass through your body every second.

The Solar Neutrino Problem

Raymond Davis built a "telescope" to look for these neutrinos.

In a tank of 100,000 gallons of perchloroethylene (cleaning fluid) in the Homestake Gold Mine, he looked for the tiny* fraction of solar neutrinos that trigger the reaction

$$\nu + {}^{37}\mathrm{Cl} \Rightarrow {}^{37}\mathrm{Ar} + e\ .$$

The above isotope of argon is unstable; it can be detected via its radioactive decay. So, by measuring the rate at which argon atoms are produced in the sealed tank, Davis estimated how many neutrinos the Sun emits.

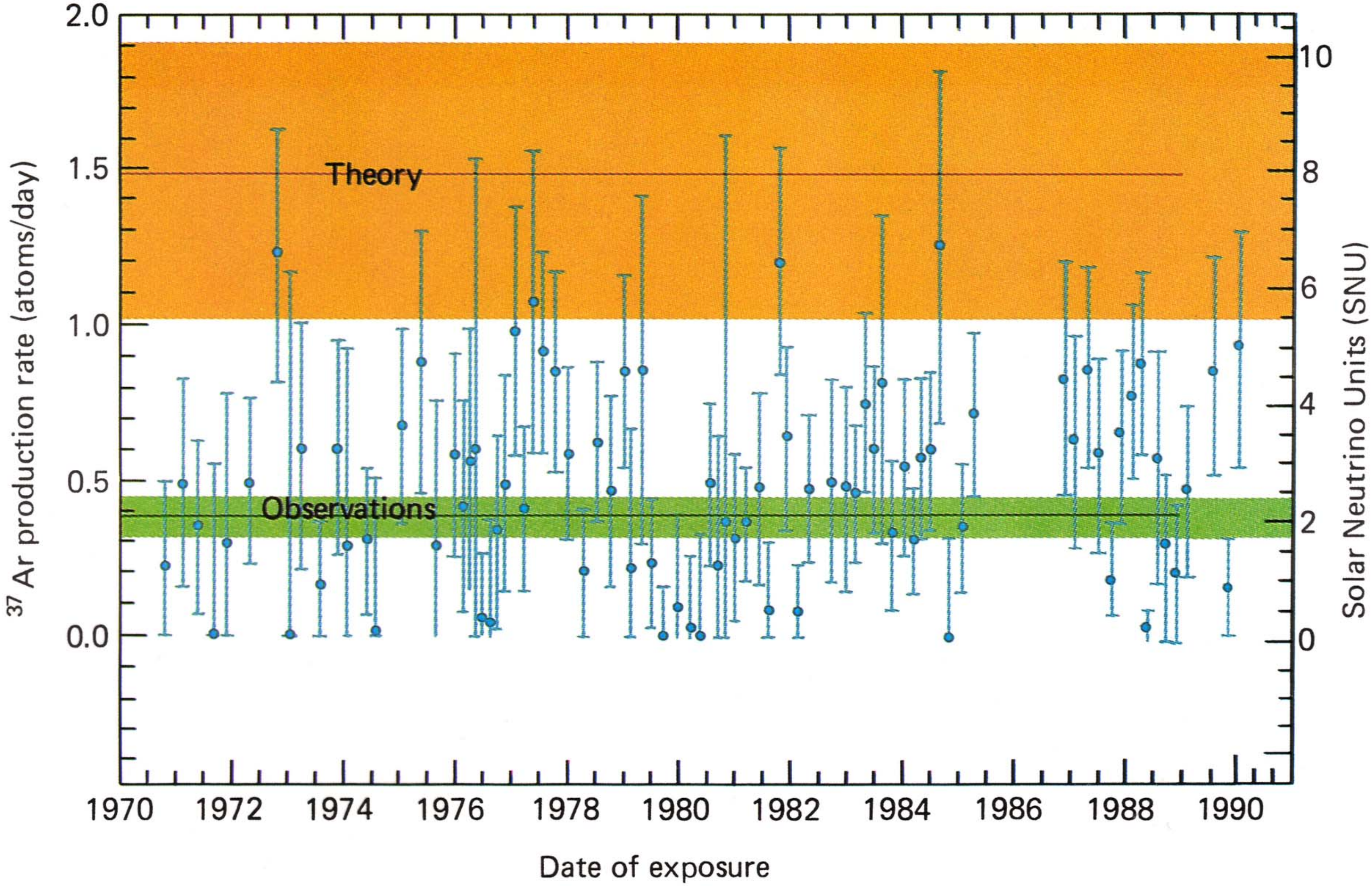
The measurement did not agree with theoretical predictions.

It looks like the Sun is making only 1/3 as many neutrinos as it should.
Or maybe neutrinos don't behave the way that we expect.

*less than one per day.

Davis Solar Neutrino Telescope

Solar Neutrino Counts



The neutrino deficiency has been confirmed by the Japanese Kamiokande II detector.

The solar neutrino problem was one of the great scientific mysteries of the late 20th century.

Astronomers wondered: Do physicists not understand neutrinos?

Physicists wondered: Do astronomers not understand the Sun?

Problem: Davis's telescope was sensitive only to very high energy neutrinos. In fact, he did not see the neutrinos from the primary p—p reactions. Instead, he detected neutrinos from subsidiary reactions that happen only 0.25 % of the time. But newer detectors confirm Davis's result.

The solar neutrino problem stimulated superb research.

Physicists now have the answer. It turns out that there are three kinds of neutrinos. Only one kind is produced by the Sun, and only this kind is seen by Davis's telescope. But if neutrinos have a small mass, then each kind of neutrino can change ("oscillate") quickly into the other kinds. By the time they get to us, the solar neutrinos would have divided themselves up equally among the three kinds. This possibility is interesting because massive neutrinos are extremely important for cosmology.

Super Kamiokande has clearly detected oscillation in neutrinos produced when high-energy particles from space collide with atoms in the Earth's atmosphere.

Super Kamiokande II has detected evidence for non-zero neutrino masses.

Raymond Davis (left) and Masatoshi Koshiba (head of the Kamiokande team that detected neutrinos from Supernova 1987A) won the 2002 Nobel Prize in Physics.
See: http://www.nobel.se/physics/laureates/2002/

Takaaki Kajita

Arthur B. McDonald

Takaaki Kajita and Arthur B. McDonald won the 2015 Nobel Prize in Physics for the discovery of neutrino oscillations, which shows that neutrinos have mass.

Detecting solar neutrinos
confirms
that the Sun is powered
by nuclear fusion.

Life Expectancies of Stars

$$\text{Life expectancy } T = \frac{\text{amount of fuel}}{\text{rate of fuel consumption}} = \frac{M}{L}$$

But the mass-luminosity relation is $L \propto M^{3.5}$

Therefore $T \propto M/M^{3.5} = 1/M^{2.5}$.

Stellar lifetime $\propto 1/M^{2.5}$.

Solar models show that the Sun will live for 10 billion years.
Therefore a 10 $M_\odot$ B2 star will live for about 31 million years.
An M5 dwarf (0.21 $M_\odot$) such as Proxima Centauri
will live for about 500 billion years.

Stellar Lifetime = $1/M^{2.5}$

If mass and luminosity are in Solar units:

Spectral Type	Mass	Luminosity	Lifetime (10^9 years)
O5	40.	405,000	0.001
B0	15.	13,000	0.011
A0	3.5	80	0.44
F0	1.7	6.4	2.7
G0	1.1	1.4	8.
K0	0.8	0.46	17.
M0	0.5	0.08	56.

56 billion years is about
4 times the age of the Universe!