- Next section:

  Central Temperature of Stars

  Stellar Energy Sources

  Stellar Lifetimes

  Properties of the Sun

  Star Formation

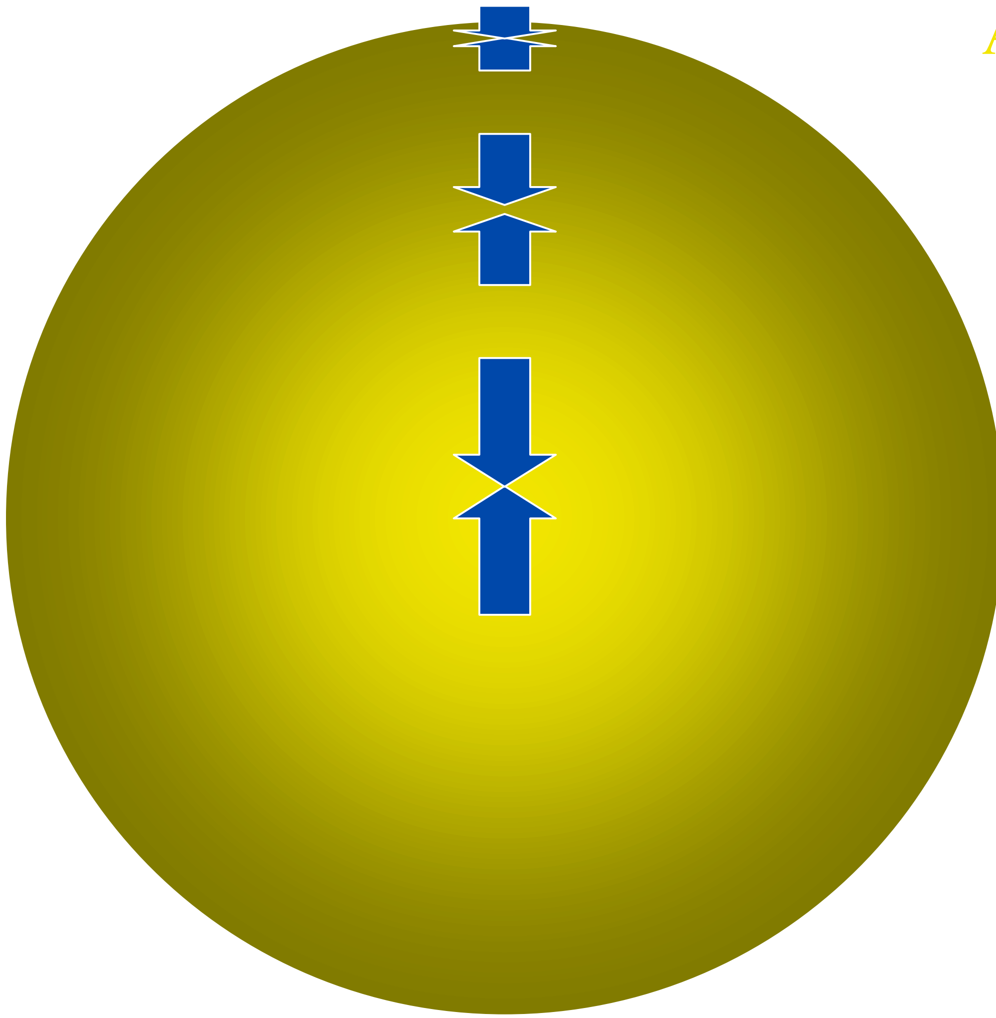
  Evolution of low-mass Stars

Stellar Structure and Central Temperature

- We can determine another property of stars by using a model of <u>Stellar Structure</u>.
- The basic principle is that stars are in

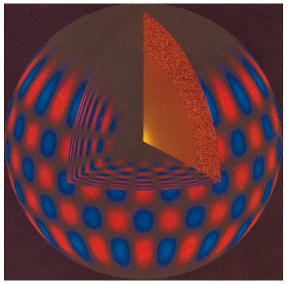
<u>Hydrostatic Equilibrium</u>

Hydrostatic Equilibrium



At each radius
$P_{grav} = P_{thermal}$

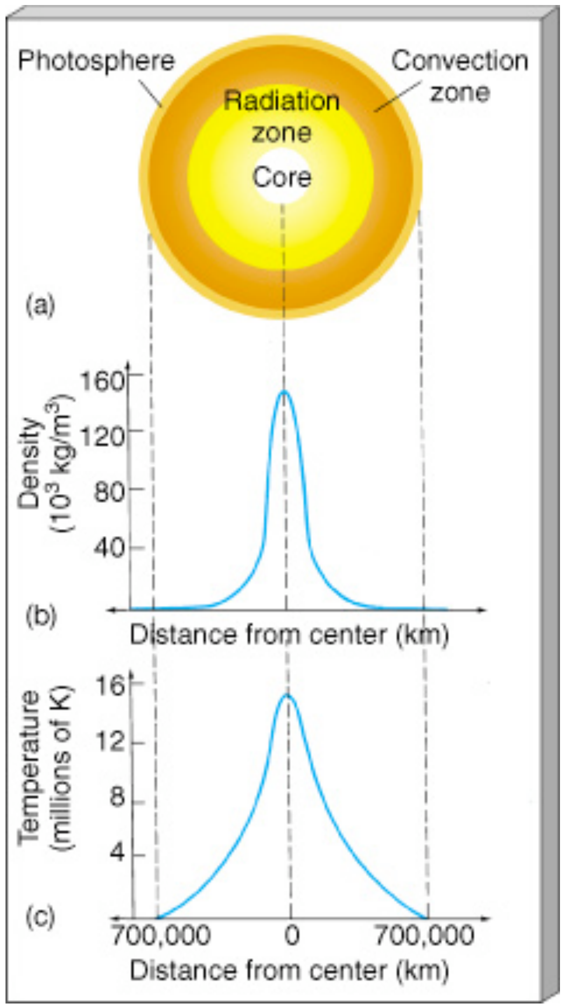
As the weight of
Overlying material
Goes up, the
Temperature needs
To go up to keep
To pressure balance



The Structure of the Sun

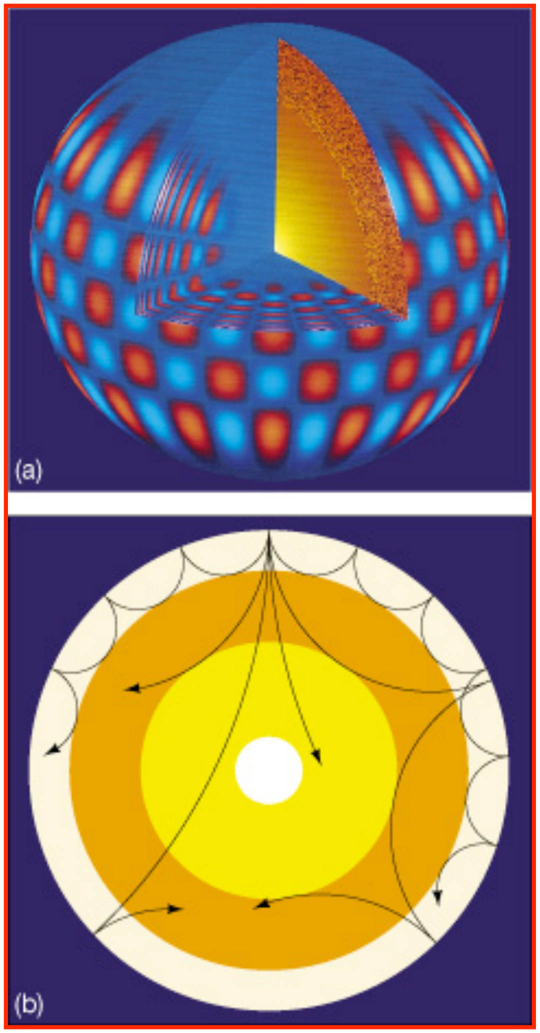
- Build a model of the Sun in hydrostatic equilibrium and you will predict the *Temperature* and *Density* as a function of radius. You need to have a relationship between pressure, temperature and density -- this is called the Equation of State.
- The first stellar structure models were constructed in the late 1950s. With computers you can do this surprisingly easily. In the graduate level Astronomy course called `Stellar Structure and Evolution' all the students build their own stellar model.

Solar Model

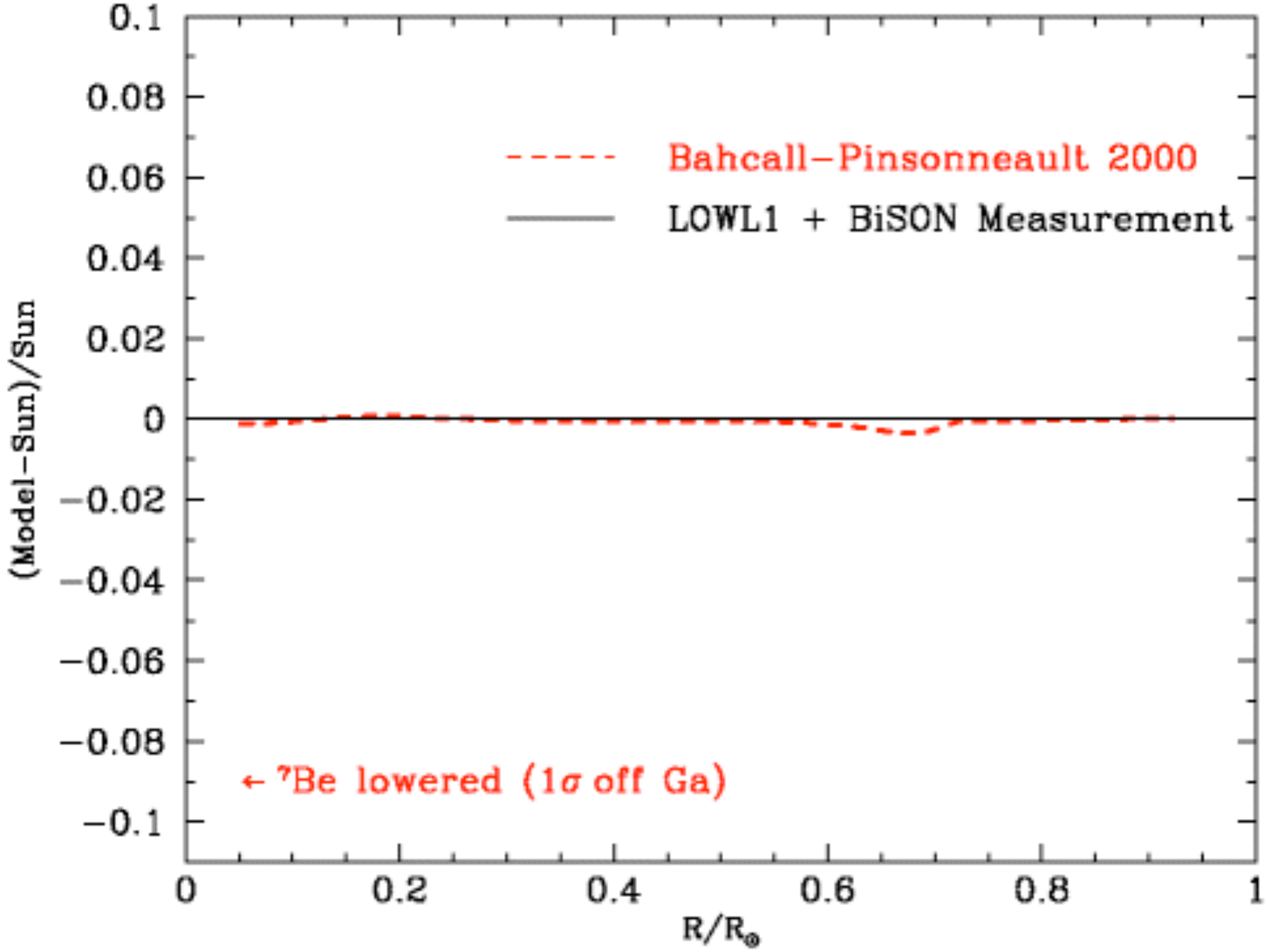


- Hydrostatic models for the Sun predict the central temperature to be about 16 x 10^6K.
- Some interesting things happen at this temperature! On Earth the only time this temperature has been reached is when H-bombs were exploded.

Helioseismology



- There were reasons to believe that we had pretty good solar models but we received unexpected superb confirmation of this in the 1990s when the `five minute' oscillations of the Sun were discovered.



Bahcall–Pinsonneault 2000
LOWL1 + BiSON Measurement
← ⁷Be lowered (1σ off Ga)
(Model−Sun)/Sun
R/R⊙

Energy Source for Stars

- A really good question is `how do stars produce all that luminous energy'
- The answer should also naturally explain the main-sequence and the mass-luminosity relation.
- Let's start with the Sun. Requirements are:

  (1) $L=4x10^{33}$ ergs/sec

  (2) for ~4.5 billions years

Coal or Wood Burning

- What is `burning'? The conversion of molecular binding energy into heat.

Coal burning efficiency: $\boxed{4 \times 10^{12} \text{ergs/gram}}$

A 3000 gram bucket of coal will generate

$$\boxed{1.2 \times 10^{16} \text{ ergs} = 300 \text{ kilowatt-hrs}}$$

which would power a little space heater for about 12 days or a 100 watt light bulb for 125 days.

Coal Burning

- Suppose all 2 x 10^{33}grams of the Sun are coal. The total energy you could generate would be:

$$\boxed{E_{total} = \left(4 \times 10^{12} \frac{ergs}{gram}\right) \times \left(2 \times 10^{33}\, grams\right) = 8 \times 10^{45}\, ergs}$$

- That's a lot of energy! At the rate of L_o, how long would the Sun last?

Coal Burning Lifetime

$$\boxed{t = \frac{8\times10^{45}\,\cancel{ergs}}{4\times10^{33}\,\frac{\cancel{ergs}}{\sec}} = 2\times10^{12}\sec = 63000\,years}$$

- If you were not sure of the right equation, remember dimensional analysis!
- By the mid-1800s it was recognized that the Earth was at least *millions* of years old.
- Note: L_o is equivalent to 1 ton of coal burned per second per square foot of the solar surface.

Gravitational Potential Energy

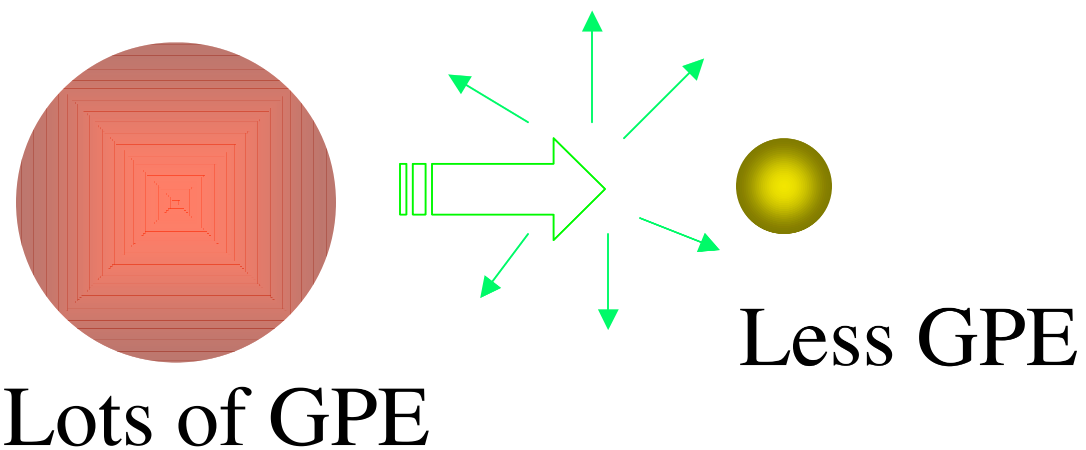
- Anytime you have a collection of mass, there is associated gravitational potential energy (GPE). For a sphere of gas (like a star for example) the GPE is given by:

$$\boxed{GPE = -\frac{5}{3} \times G \times \frac{M}{R^2}}$$

- Where R is the radius of the sphere, M is the mass and G is the universal gravitational constant.

GPE

- Imagine a large gas cloud that shrank in radius at constant mass.



- Difference in GPE (actually 1/2 of it) must be released as E-M radiation during the shrinking.

GPE

- Note that we are familiar with this idea based on life on Earth. A piano on the edge of a cliff has more GPE than it has at the bottom of the cliff (it is at a larger R from the center of the Earth).
- Drop the piano and this GPE is converted into kinetic energy, then into sound waves, breaking molecular bonds and heat.

GPE efficiency

- We can calculate the GPE of the Sun from the formula a few slides back:

$$\boxed{GPE_{Sun} = 2 \times 10^{48}\, ergs}$$

- If we could extract this amount of energy for radiation (by letting the Sun shrink) it would yield:

$$\boxed{Eff(gpe) = \frac{2 \times 10^{48}\, ergs}{2 \times 10^{33}\, grams} = 10^{15}\, \frac{ergs}{gram}}$$

GPE

- This is 250 times more efficient than chemical burning, but if you do the lifetime calculation again:

$$\boxed{t = \frac{2 \times 10^{48}\, ergs}{4 \times 10^{33}\, ergs/\sec} = 5 \times 10^{14} \sec = 16 \times 10^{6}\, years}$$

- Still too short! (Plus the Sun would have to have been much larger in the past)

GPE

- A variant of this method was considered a serious possibility until the early 1900s. Comets falling into the Sun would make a good energy source. Only need about 1 Earth mass per year . The mass of the Sun would be increasing, and there is no evidence from changes in the Earth's orbit to support this idea.

Nuclear Power

- The answer for the power source of the Sun had to await the discovery of the nucleus and the nuclear force.

Forces of Nature

- First, let's review the fundamental forces.

  (1) <u>Gravity</u> is an attractive force between objects with mass. This keeps you in your seat, keeps the Earth in orbit around the Sun, prevents the hot gases in the Sun from expanding away into space and other useful stuff.

  This is the weakest of the fundamental forces.

Forces of Nature

(2) <u>Electric Force</u> between electrically-charged objects (protons and electrons).

Like charges Repel, opposite charges Attract. This is the force that holds atoms and molecules together and is useful for running nifty gadgets. It is also the reason that you don't fall through the floor and get cooked in the middle of the Earth.

Chemical burning is converting electrical forces into E-M radiation.

Forces of Nature

(3) <u>Weak Nuclear Force</u>. This is responsible for radioactive decay of some nuclei.

(4) <u>Strong Nuclear Force</u>. This is an attractive force between nucleons and it is what binds protons and neutrons together in the nuclei of atoms

Which force is stronger, electric or nuclear strong force?

Must be the nuclear strong force! The protons in a nucleus repel one another, yet nuclei are not flying apart. In fact, the Nuclear strong force would right this minute be binding everything in the Universe into a tiny ball except for the fact that is only acts over <u>VERY TINY</u> distances.

The Four Forces

- Note that Gravity is MUCH weaker than the electric force or the strong nuclear force. Comparing the electric repulsion of two protons to their gravitational attraction, gravity is weaker by a factor of 10^{36}.
- So, why is gravity the force we see dominating the Universe?

Energy from the Nuclear Force

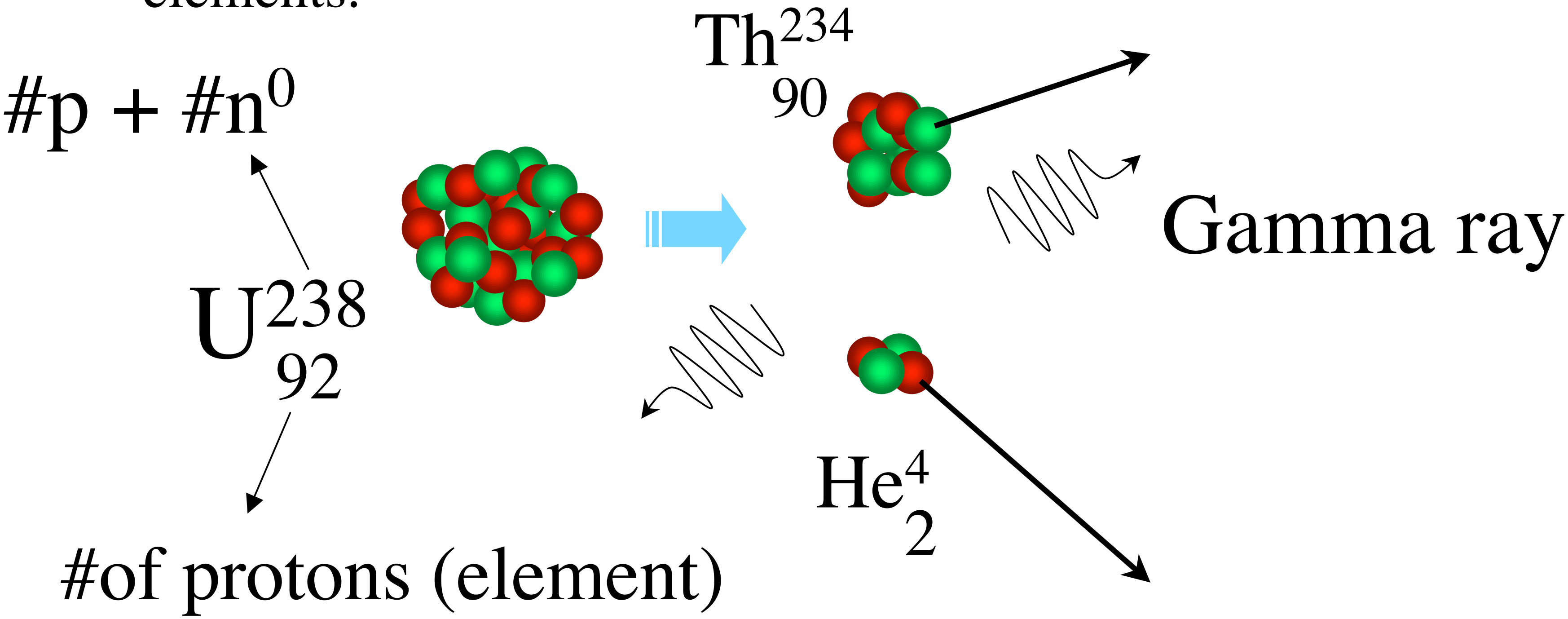
- There are two paths to deriving energy from nuclear reactions (a nuclear reaction is adding or subtracting a proton or neutron from a nucleus).

(1) Nuclear Fission

(2) Nuclear Fusion

Nuclear Fission

- There are some elements in the Periodic Table that spontaneously fall apart. These are the <u>radioactive</u> elements.



Nuclear Fission

$$\boxed{U^{238} \Rightarrow Th^{234} + He^{4}}$$

There is a remarkable thing!

$$\underline{\underline{\text{Mass}(U^{238}) > \text{Mass}(Th^{234}+He^{4})}}$$

Mass Defect

- Even though there are the same number of nucleons before and after, a little mass disappeared in the reaction. This mass is associated with the difference in Nuclear Binding energy before and after.
- The missing mass has been converted into energy via everyone's favorite physics equation!

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

In this application, `m' is the mass that went missing and `E' is the energy released in the form of gamma rays. For some fission reactions, the amount of energy released per gram of missing mass is large.

Nuclear Fission

Fission can release as much as

$\boxed{10^{18} \text{ ergs/gram}}$

Recall, coal burning released

$\boxed{4 \times 10^{12} \text{ ergs/gram}}$

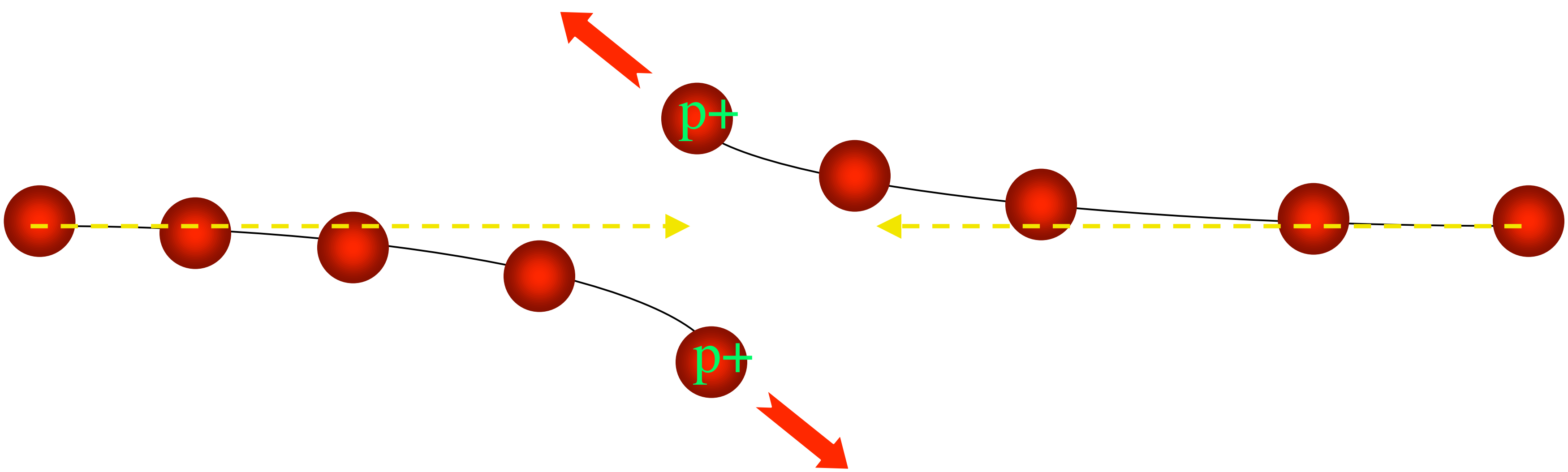
- Nuclear fission could produce enough energy to fuel the Sun for ~6 x 10^{10} years <u>IF</u> the Sun were composed completely of fissionable material.
- It is not! For example, the Uranium abundance in the Sun is less than a millionth of the solar mass.

Nuclear *Fusion*

- Imagine a gas of protons (p+). At `low' temperatures the electrical repulsion force prevents the close approach of two p+
- But as T increases, the minimum approach distance decreases and some p+ get close enough (10^{-15}m) for the short-range, but VERY STRONG nuclear force to bind them together.

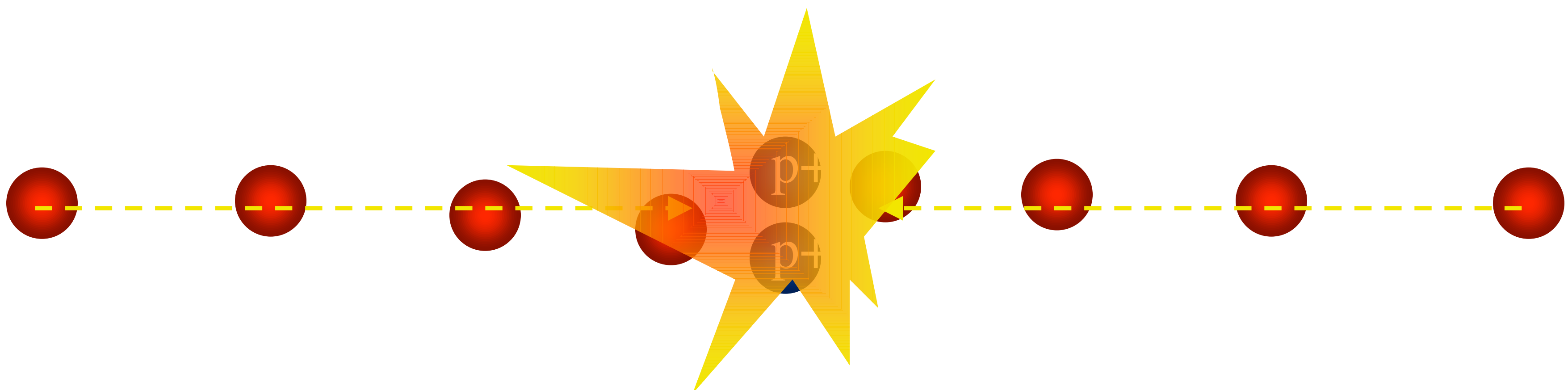
Hydrogen (proton) fusion

Like electrical charges repel. So, protons in a gas *avoid* `collisions'

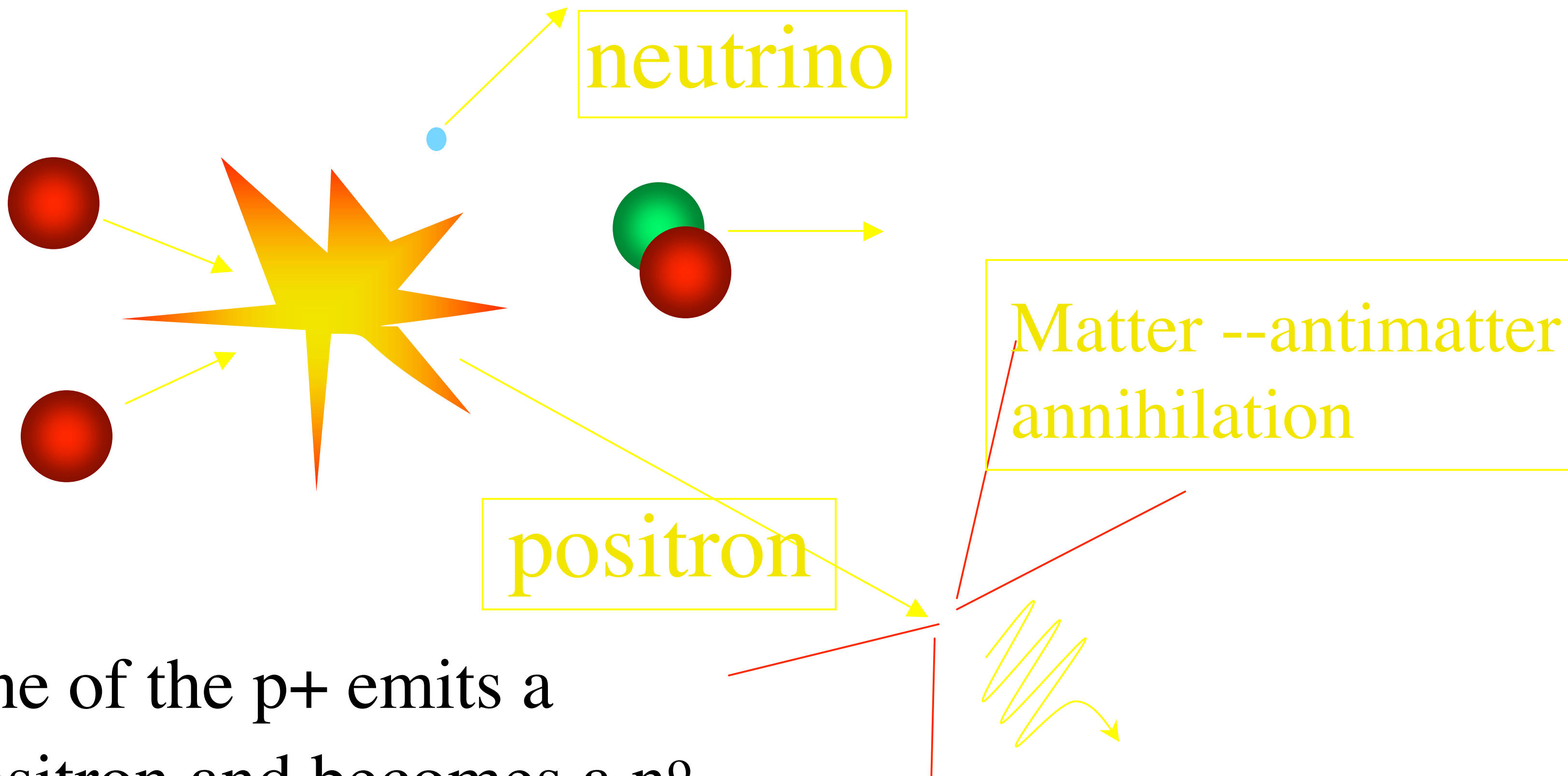


Hydrogen (proton) fusion

However, as a gas temperature goes up, the average speed of the particles goes up and the protons get closer before repelling one another. If the proton get very close, the short-range *nuclear force* fuses them together.



Hydrogen Fusion

- Proton fusion involves some interesting ideas.
- 

One of the p+ emits a
<u>Positron</u> and becomes a n^o

Hydrogen Fusion

When two protons fuse, almost immediately one turns into a neutron by emitting a positively charged electron (known as a positron and `beta-decay'). The e^+ is antimatter (!) When it comes into contact with its matter partner (e^-) it annihilates entirely into energy.

What element has a nucleus with 1 proton and 1 neutron? <u>Deuterium</u> (heavy hydrogen)

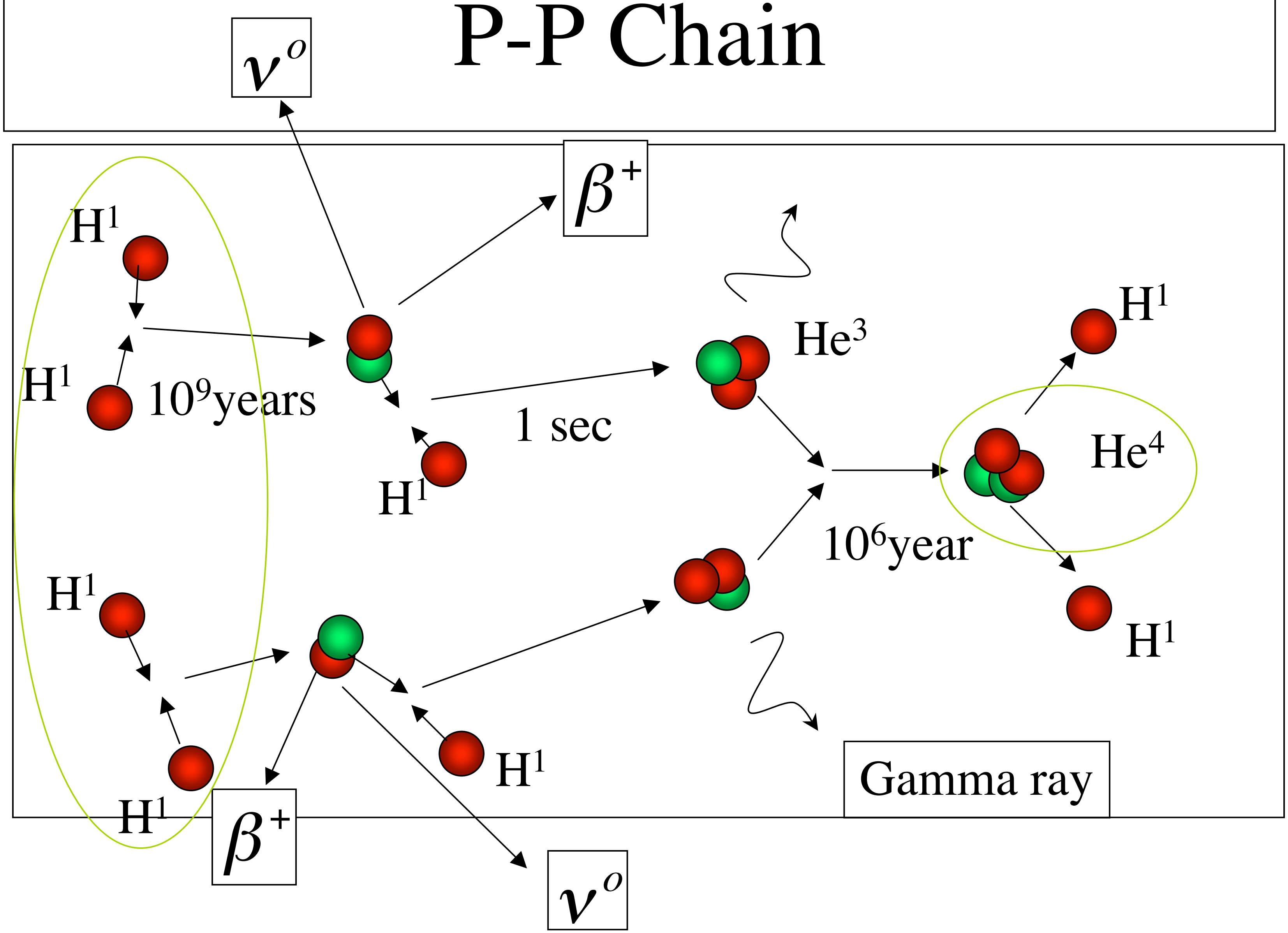
Neutrinos

- Another curious particle that flies out of the reaction is called a `neutrino' (little neutron).
- This is a chargeless, perhaps massless particle which has a tiny crossection for interaction with other types of matter. The mean free path in lead is five light years.
- Neutrinos were first postulated in 1932 to account for missing angular momentum and energy in beta-decay reactions (when a proton becomes a neutron and emits a positron).
- Neutrinos are <u>leptons </u>- subatomic particles that participate in weak interactions, but not the strong nuclear force.

Neutrinos

- The Sun emits about 10^{38} neutrinos/sec.
- Humans emit about $3x10^{8}$ neutrinos/day (radioactive potassium).
- Every second we have many neutrinos pass through our bodies: 400,000 billion from the Sun, 50 billion from the Earth and 100 billion from nuclear power plants.

P-P Chain



ν^o
β^+
H^1
H^1
10^9years
H^1
1 sec
He^3
H^1
He^4
10^6year
H^1
H^1
H^1
H^1
Gamma ray
H^1
β^+
ν^o

P-P Chain

- The net result is

$$\boxed{4H^1 \text{ --> } He^4 + \text{energy} + 2 \text{ neutrinos}}$$

where the released energy is in the form of gamma rays.

The source of the energy is again a tiny bit of mass that goes missing:

Mass(4H) = 6.6943×10^{-24} grams

Mass(He^4) = 6.6466×10^{-24} grams

P-P Chain

- The amount of missing mass is:

$$\boxed{\Delta mass = 0.048 \times 10^{-24}\ grams}$$

- The energy generated is:

$$\boxed{E = \Delta mc^2 = 4.3 \times 10^{-5}\ ergs}$$

- This much energy is released by $4H^1$ with a total mass of 6.6943×10^{-24}grams. The efficiency of hydrogen fusion is therefore:

6.4×10^{18} ergs/gram

Sun's Lifetime with H-fusion

- Total energy available:

$$\boxed{6.4 \times 10^{18} \frac{ergs}{gram} \times \left(2 \times 10^{33}\, grams\right) = 12.8 \times 10^{51}\, ergs}$$

- Lifetime of the fusion-powered Sun

$$\boxed{\frac{12.8 \times 10^{51}\, ergs}{4 \times 10^{33} \frac{ergs}{\sec}} = 3.2 \times 10^{18} \sec = 10^{11}\, years}$$

100 billion years

- This is promising!

Requirements for a Fusion-powered Sun

(1) Need lots of protons (H nuclei). ☑

Element	Abundance (#)
Hydrogen	92.0%
Helium	8.3%
Oxygen	0.06%
Carbon	0.02%
Nitrogen	0.01%
The rest	…

Requirements for Fusion-powered Sun

(2) Need a high temperature. For the p-p chain the gas temperature needs to be $>10^7$K.

- Recall the discussion about stellar structure. In the center of the Sun, hydrostatic equilibrium requires the temperature to be around 15 million K. In the center 10% of the Sun $T > 10^7$K

Fusion-powered Sun

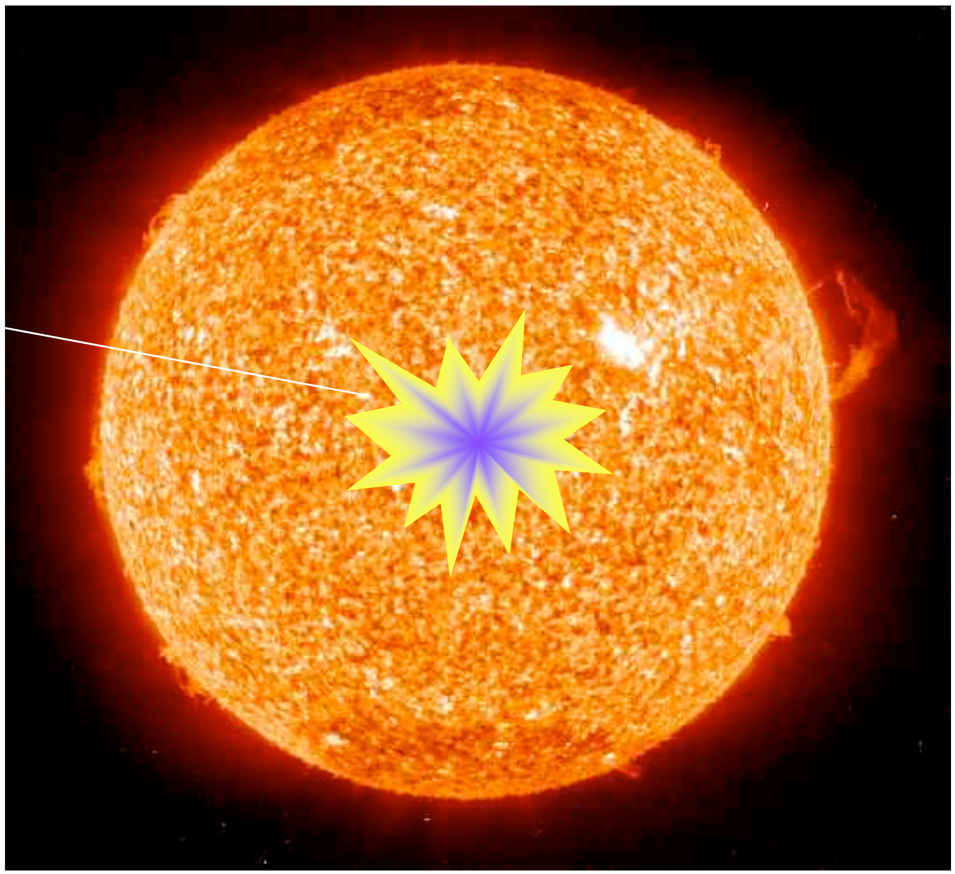
1) Lots of fuel

2) Conditions are right in the central 10% for the P-P cycle to run

3) P-P fusion is efficient enough to power the Sun for billions of years.

Looks like the Answer!

H -->He

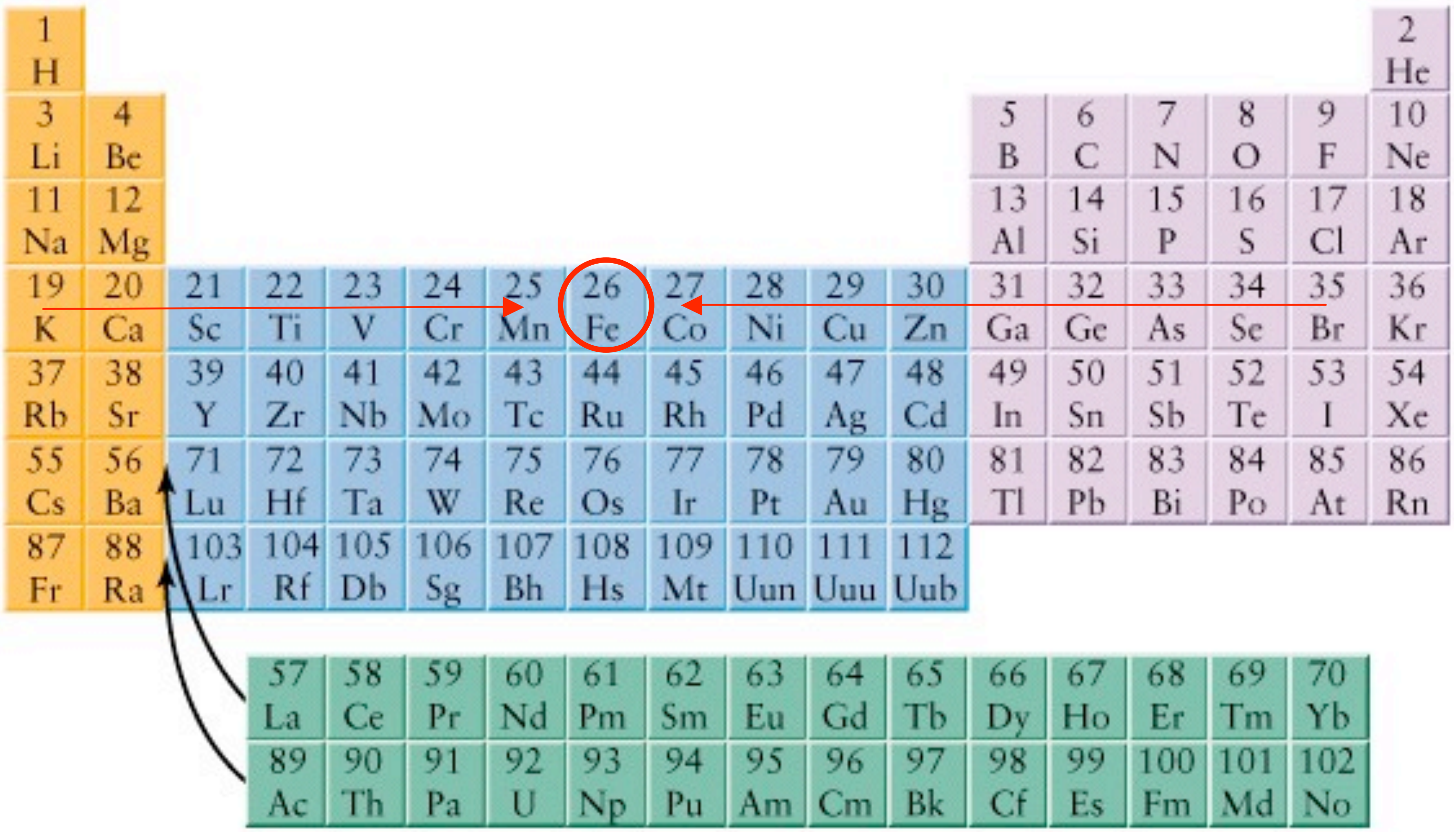


Note a small falsehood

- In the Sun, the protons don’t really get close enough for the nuclear force to be stronger than the electric repulsive force.
- Fusion in the Sun (and life on Earth) is the result of a very odd property of atomic matter called <u>Quantum Tunneling</u>.
- An analogy is me running full speed and attempting to leap over a 30-foot-tall wall. Most attempts, I crash into the wall and fall to the ground. But, once in awhile, even though I don’t leap 30’ into the air, I am successful and end up on the other side of the wall.

Fusion vs. Fission

- We’ll talk about this in more detail later, but the way nuclei are put together, you get energy released when *fusing* light elements and when heavy elements undergo *fission*. The breakpoint is iron.


1 H
2 He
3 Li 4 Be
5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg
13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Uun 111 Uuu 112 Uub
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No

Fusion-powered Sun

- An interesting aside. To produce the solar luminosity, the Sun is converting matter into energy:

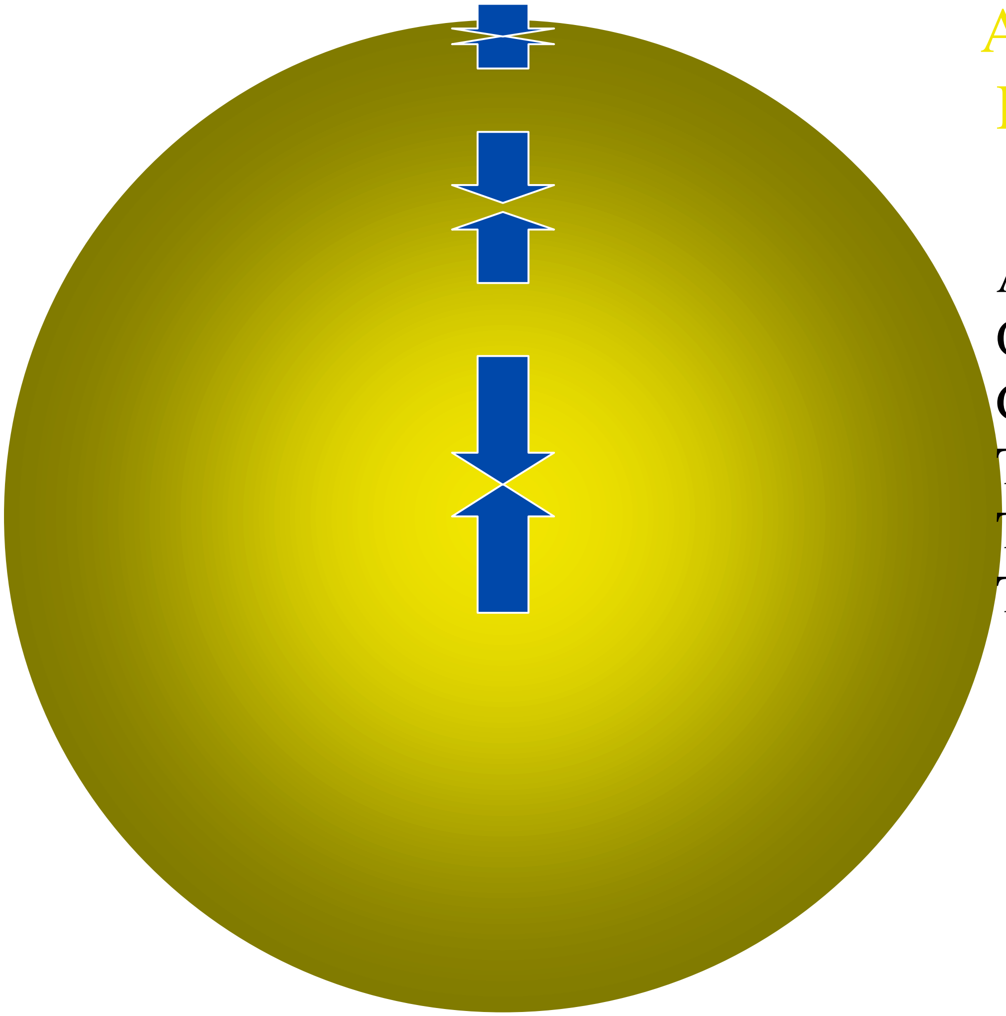
$$\boxed{4 \times 10^{33} \frac{ergs}{\sec} \times \frac{1}{6.4 \times 10^{18} \frac{ergs}{gram}} = 6.25 \times 10^{14} \frac{grams}{\sec}}$$

- This is the amount of H --> He per second. The amount of matter converted to energy is:

<u>4.3 million tons per second</u>

- Quiz 3 will be on
  - Stellar structure
  - Energy sources
  - Stellar lifetimes
  - Star formation
  - Stellar evolution for low-mass stars

Hydrostatic Equilibrium



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P-P Chain

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100 billion years

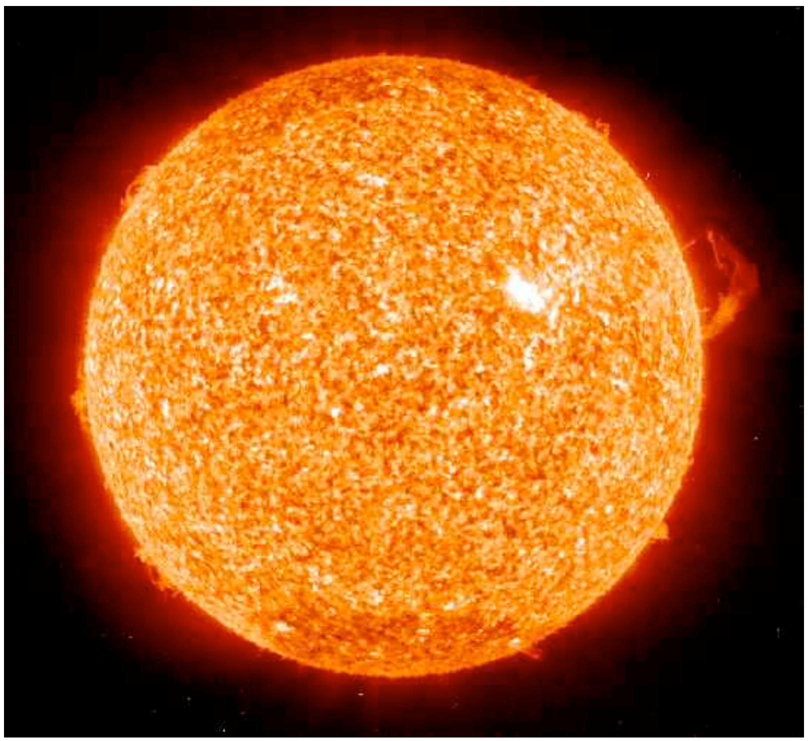
Fusion-powered Sun

1) Lots of <u>fuel</u>

2) Conditions are <u>right</u> in the central 10% for the P-P cycle to run

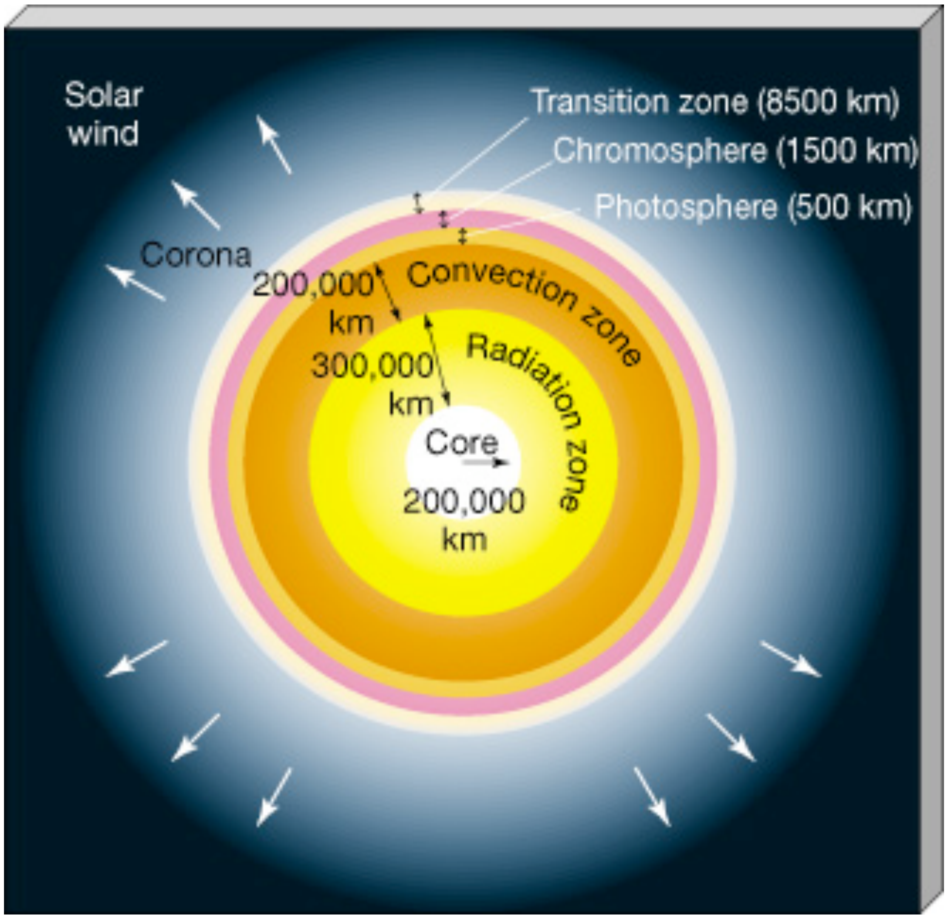
3) P-P fusion is <u>efficient</u> enough to power the Sun for billions of years.

The Sun: Our nearest star



Property	Value
Surface T	5500K
Central T	15×10^6 K
Luminosity	2×10^{33} ergs
Mass	4×10^{33} grams
Lifetime (ms)	10 billion years

Solar Structure



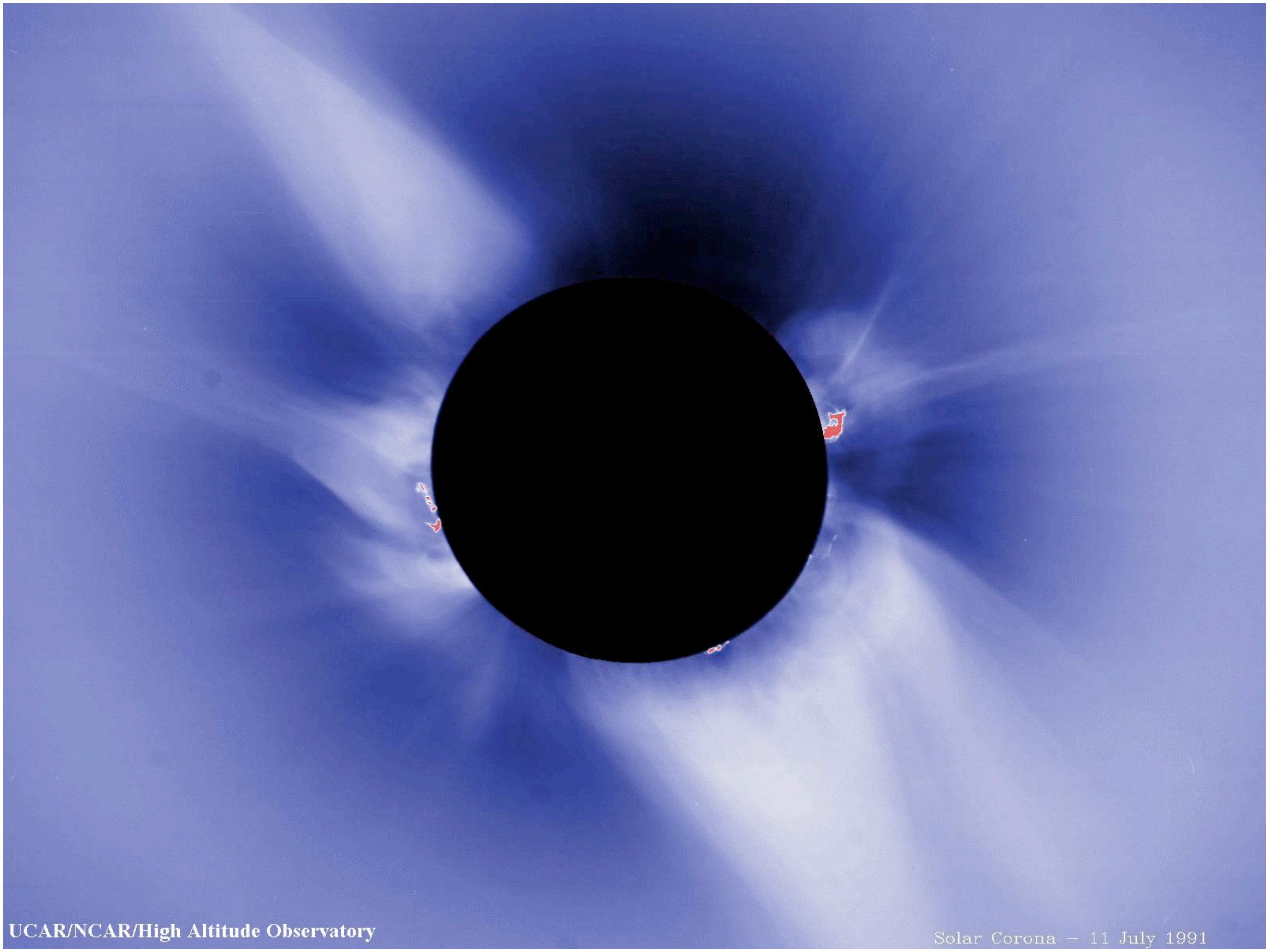
- Build a model and find the central part of the Sun has the right conditions for H fusion to He.
- Energy released in the form of gamma rays in the core is very quickly absorbed then reemitted and absorbed and …
- It takes about 180 thousand years for the energy released in H fusion to leave the surface of the Sun

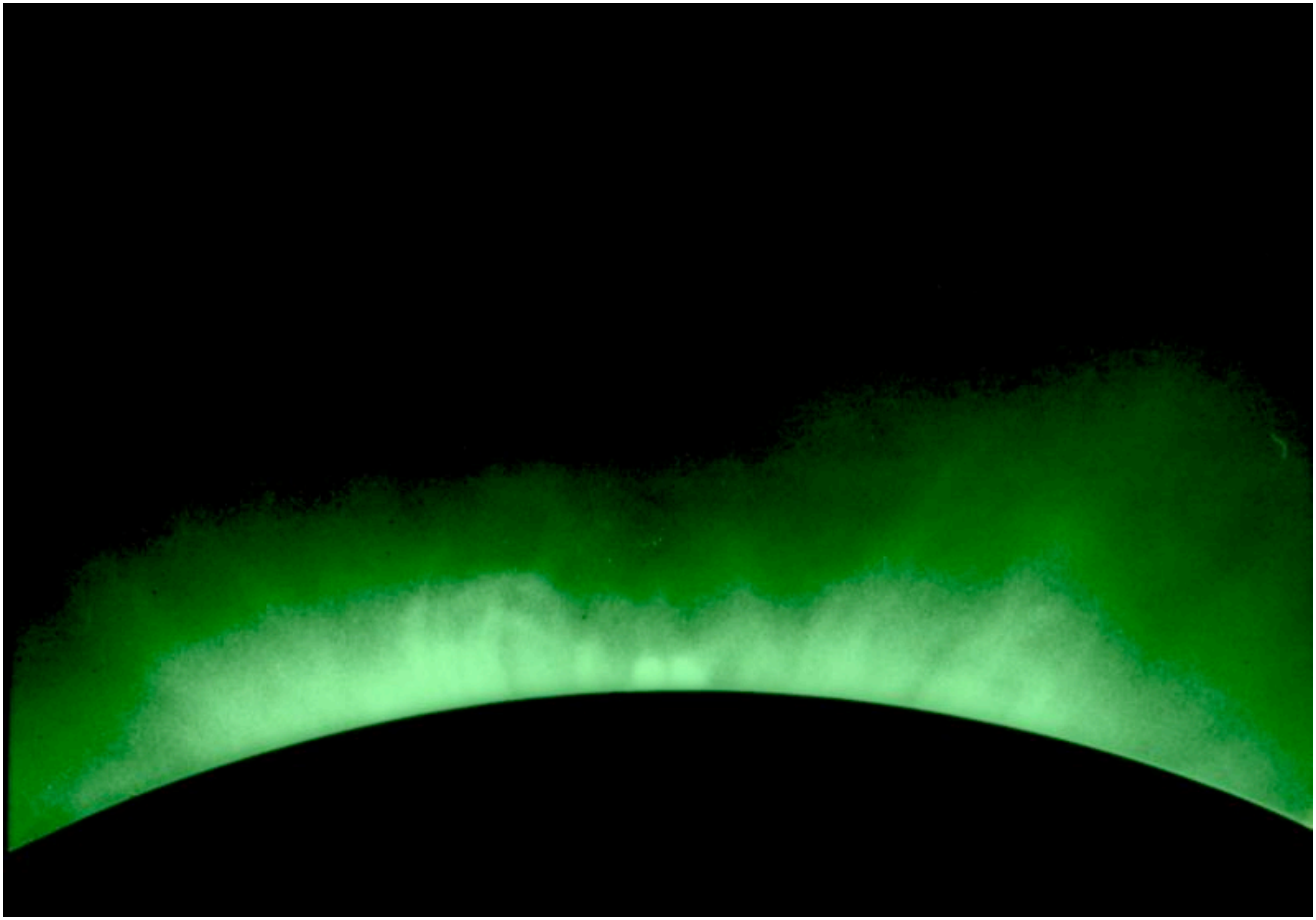
Solar Structure

- Above the core is the Radiative Zone where the photons carry all the energy outward
- Next comes the Convection Zone where the Sun becomes convectively unstable and bulk motions help to carry the energy outward.
- On top of this is the Photosphere -- this is the region where photons from below are last absorbed and the next reemited photons stream off into space.

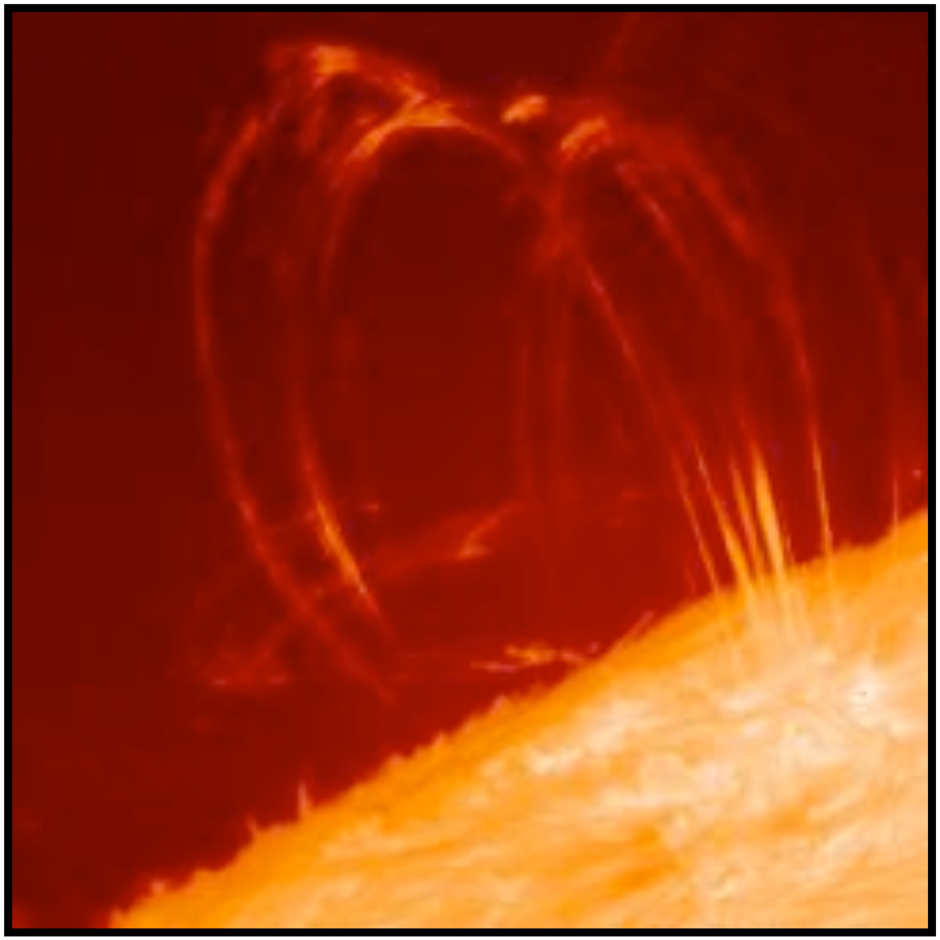
Outer Solar Structure

- The Sun's temperature reaches a minimum in the photosphere, then increases in the chromosphere and increases again into the million K regime in the corona.


UCAR/NCAR/High Altitude Observatory
Solar Corona – 11 July 1991

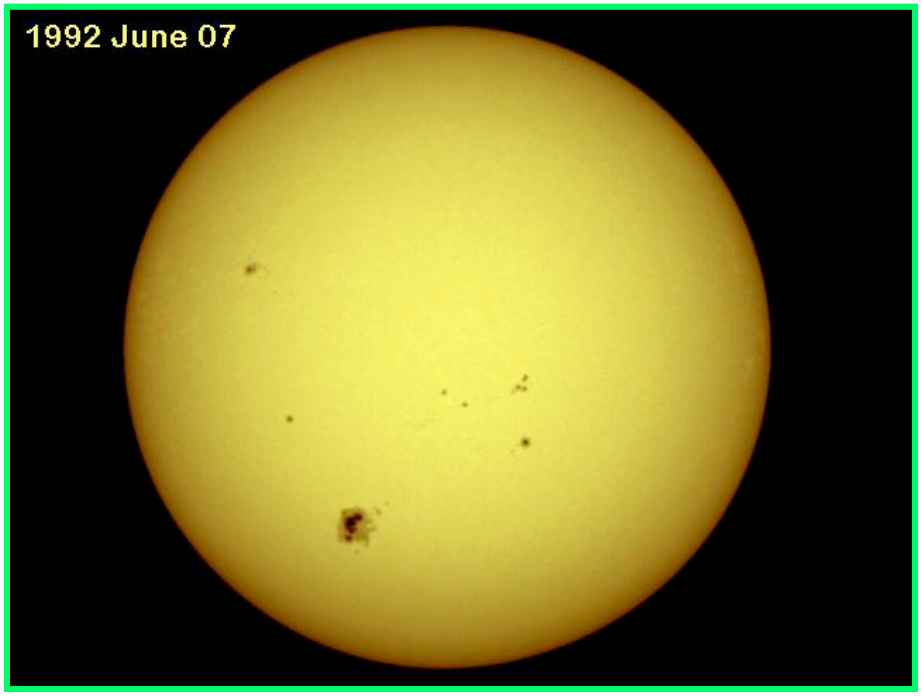


Solar Wind

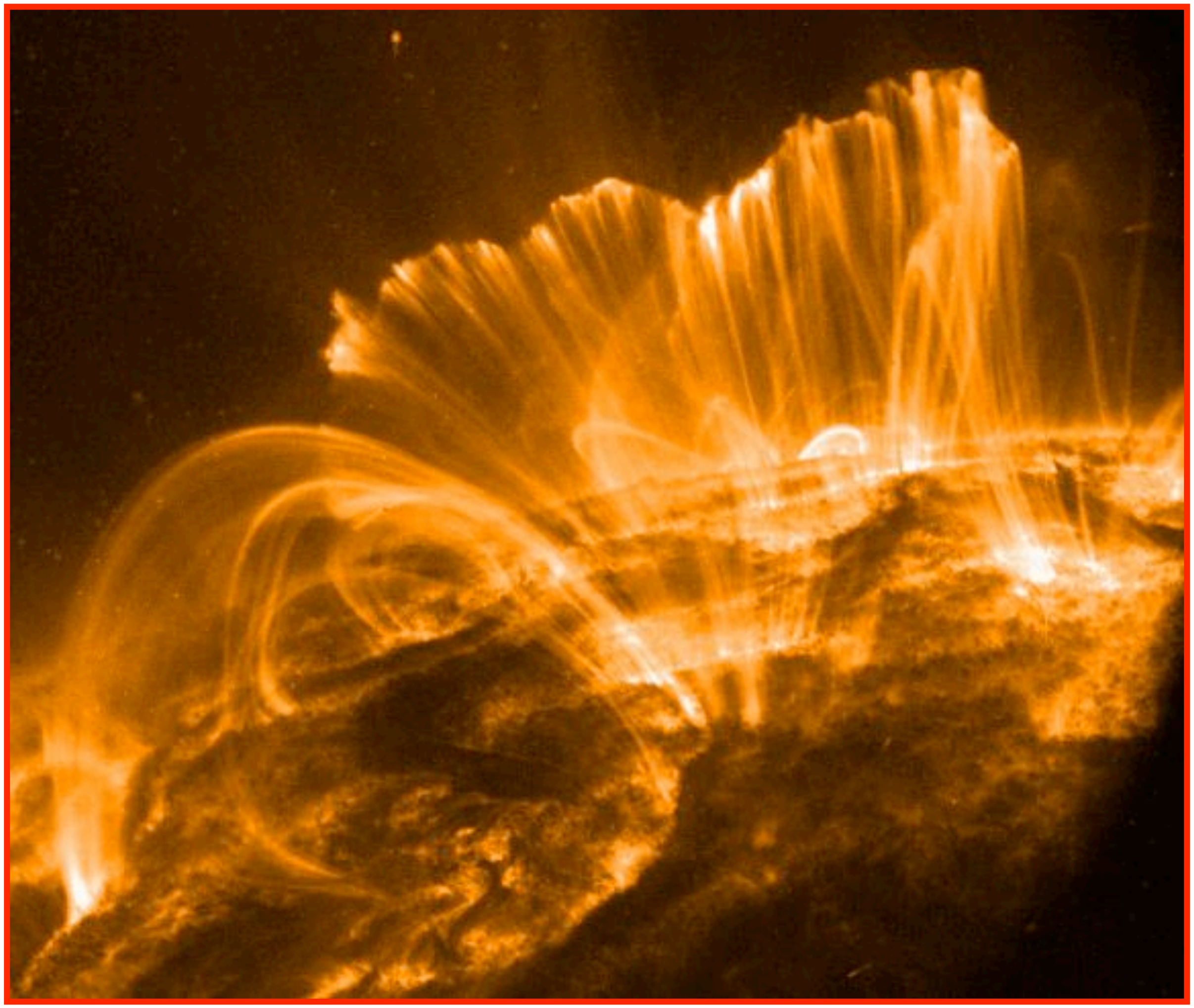


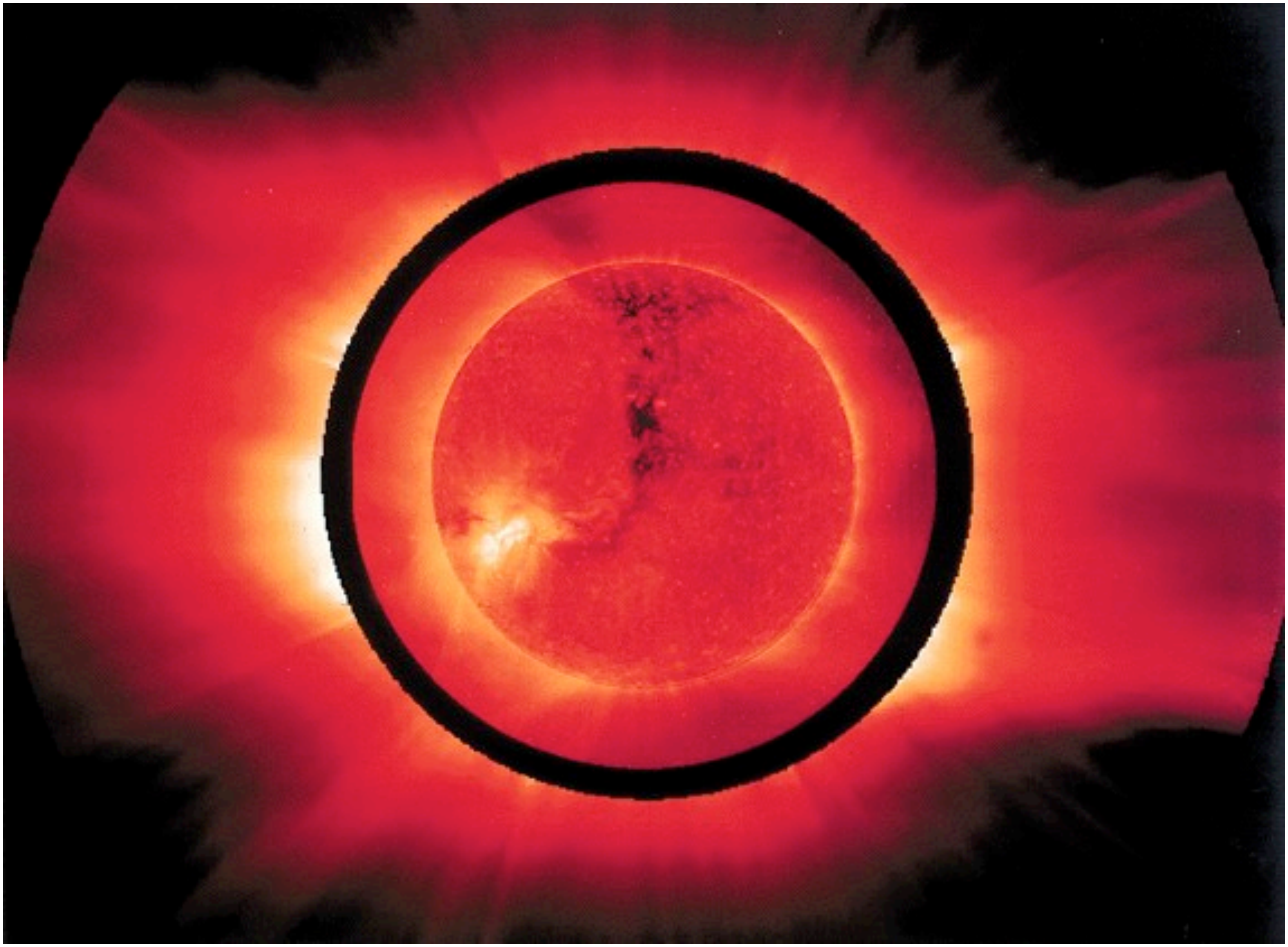
- There is one last solar phenomenon to talk about.
- Hot charged particles (mostly p+ and e-) evaporate from the Sun and stream into the Solar System.
- About 1 million tons/second stream away at *1 million mph*.

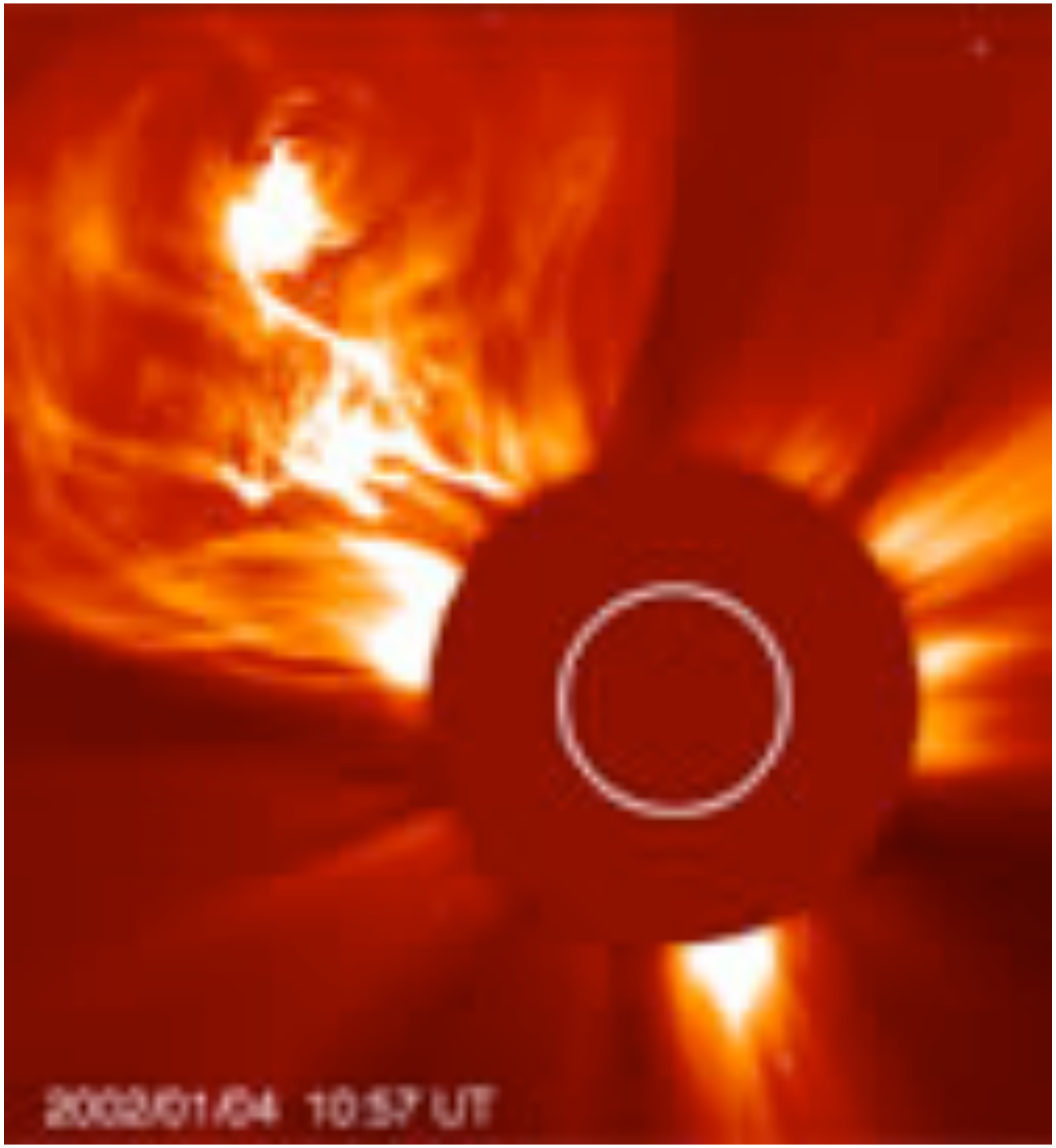
Solar Wind



- The solar wind increases in times of solar surface activity (flares) which in turn are correlated with sunspot activity.
- Solar wind `storms' can have powerful effects on the Earth.



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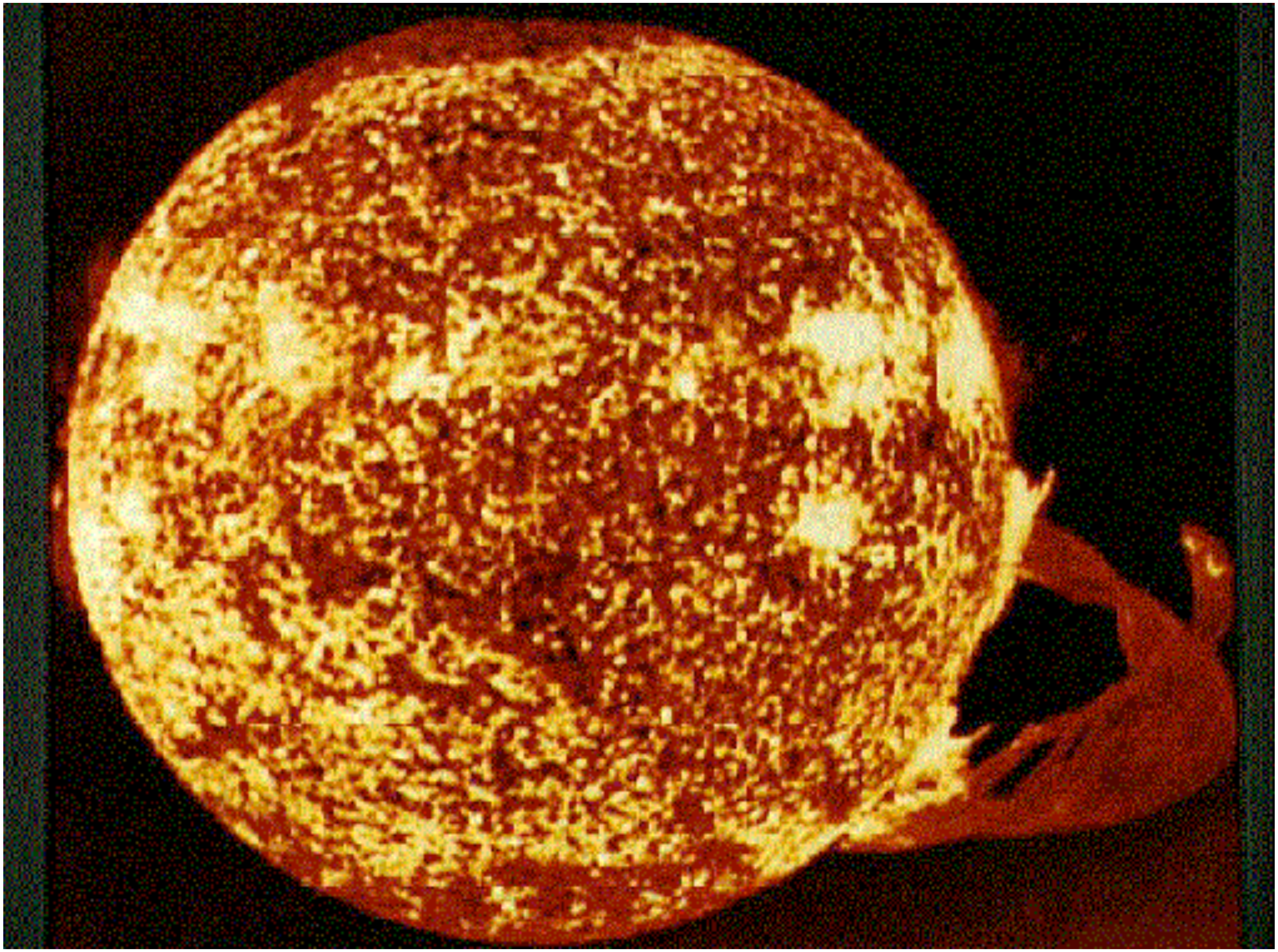
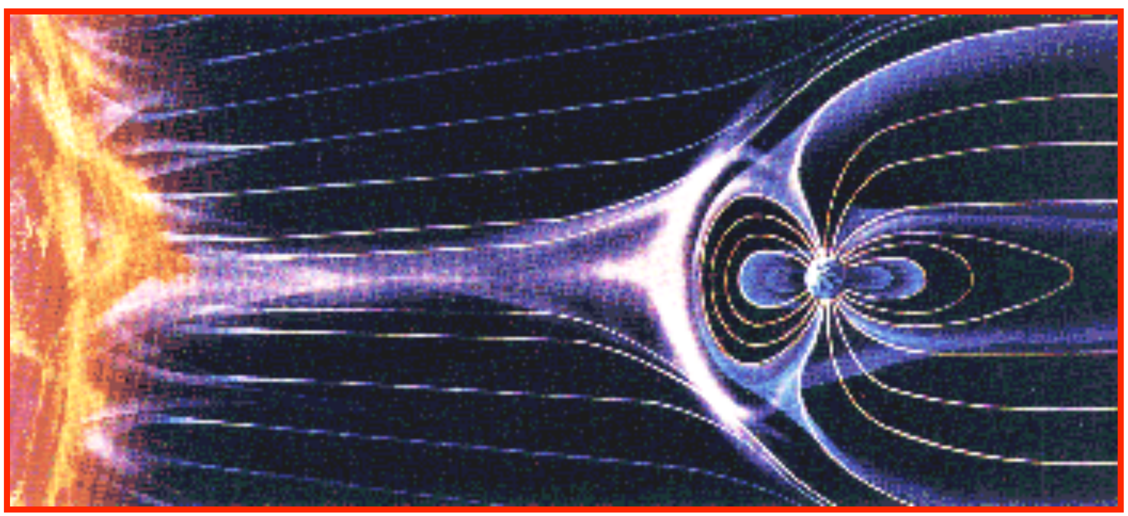


Solar Wind

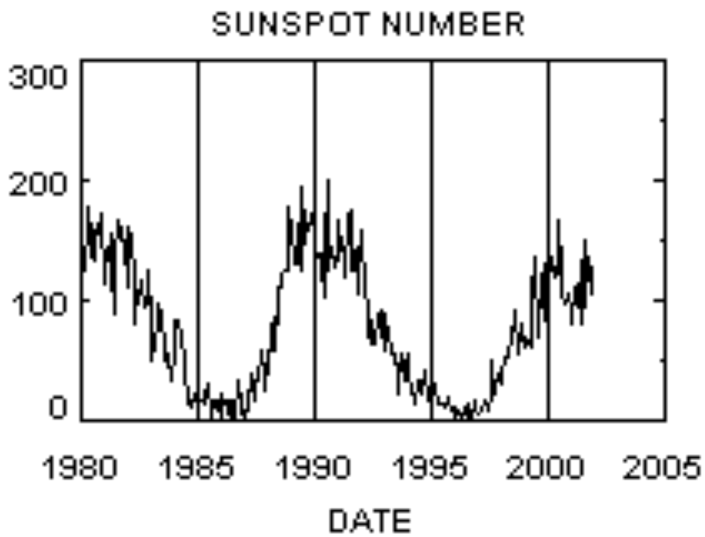
- The Solar wind (very high energy charged particles) would be very dangerous.
- Fortunately, we are protected by the Earth's magnetic field.



Solar Wind

- Moving charged particles spiral along magnetic field lines. The Solar Wind particles get funneled to the Earth's magnetic poles and stored in the `Van Allen Radiation Belts'.
- The solar wind particles crashing into atoms (mostly oxygen) in the upper atmosphere at the poles is the source of the northern and southern lights.

Solar Activity-Earth



- There is an 11-year cycle of solar activity.
- People have claimed correlations of the solar cycle with droughts, cold weather and the like.
- Maunder Minimum from 1650 - 1700 coincides with the only mini-ice age in recorded history.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Solar Wind

- Although biological organisms are pretty well protected from the solar wind, solar storms can have serious consequences.

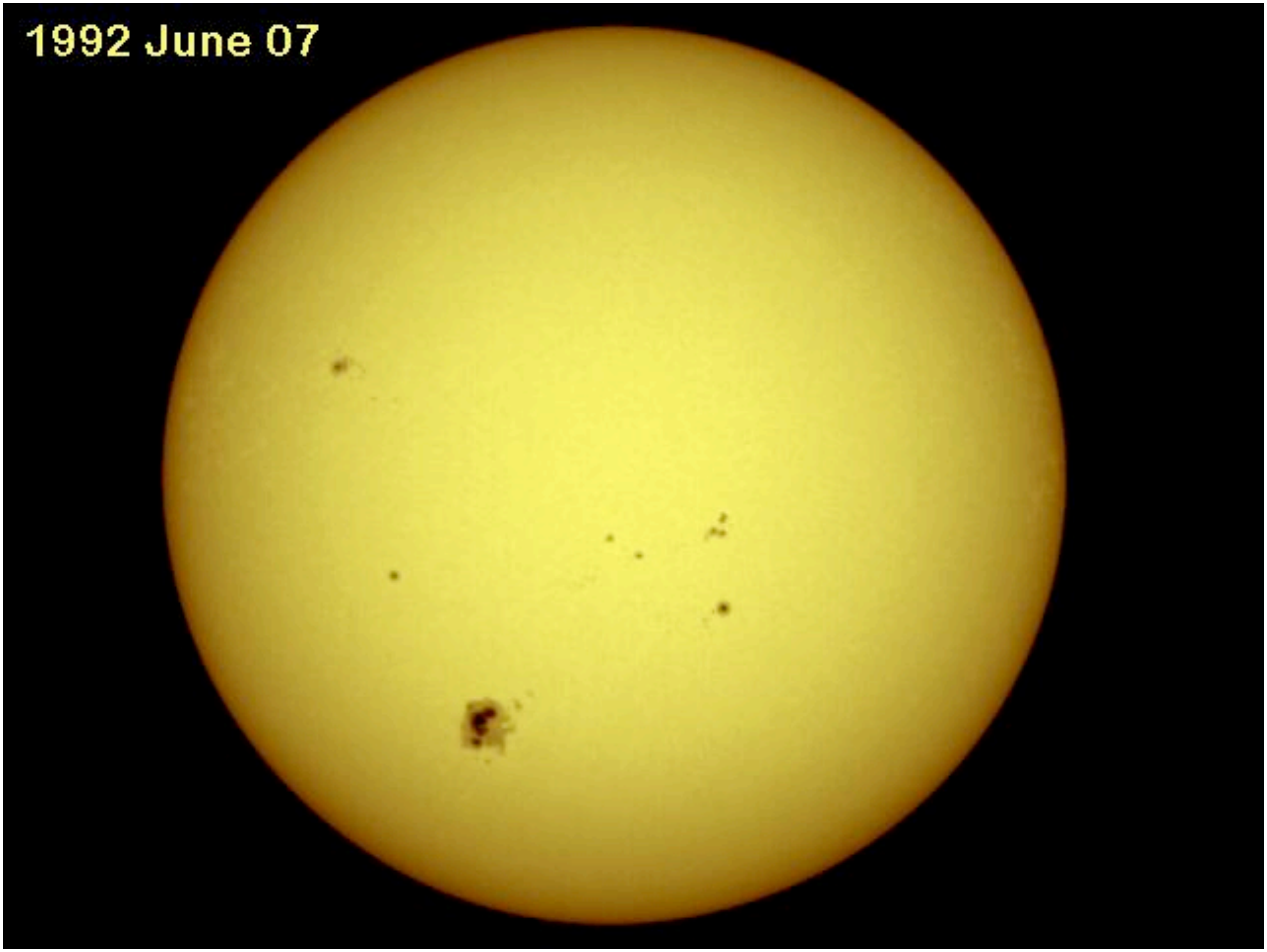
(1) The Earth's atmosphere expands

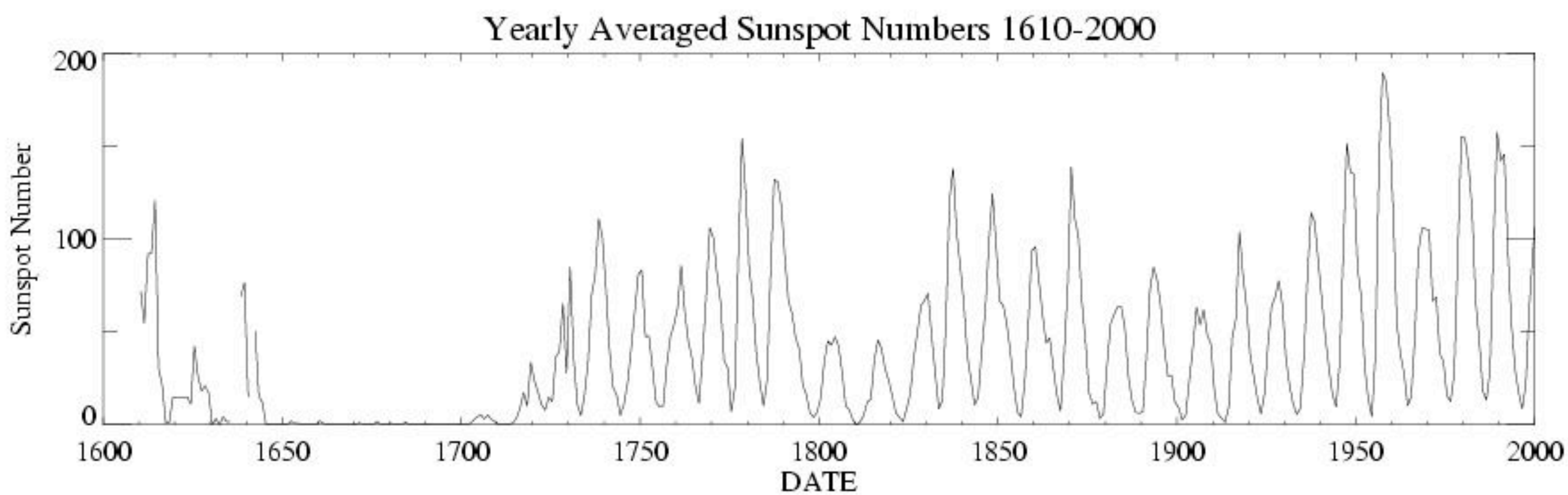
-Certain types of communications are disrupted

-Satellites can be dragged out of orbit

(2) Large currents can get induced in power grids

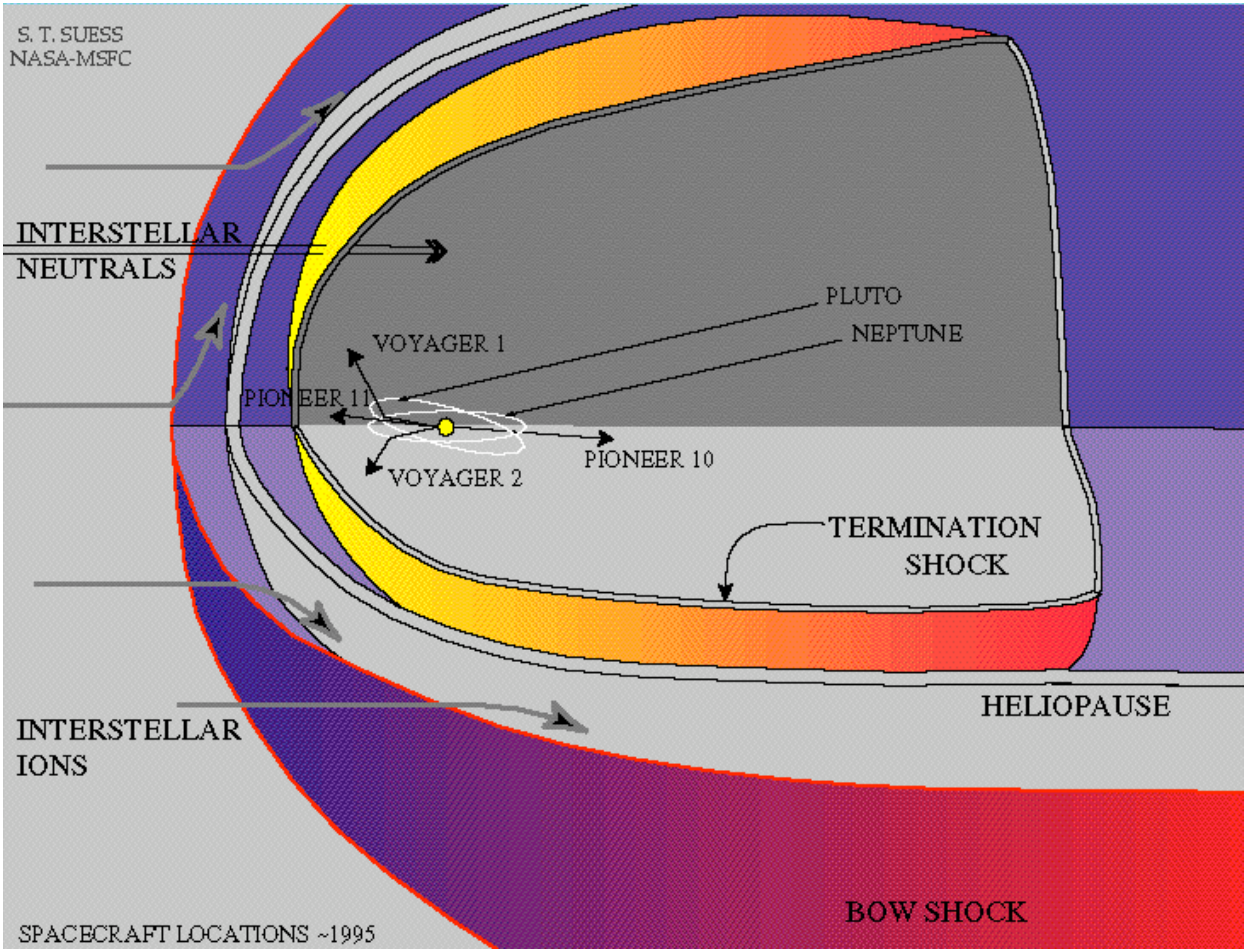
(3) There is a mysterious connection with solar activity and the Earth's weather.


1992 June 07



Yearly Averaged Sunspot Numbers 1610-2000
Sunspot Number
200
100
0
1600
1650
1700
1750
1800
1850
1900
1950
2000
DATE

The solar system is flying through the Galaxy and the solar wind interacts with the interstellar medium to create the heliosphere

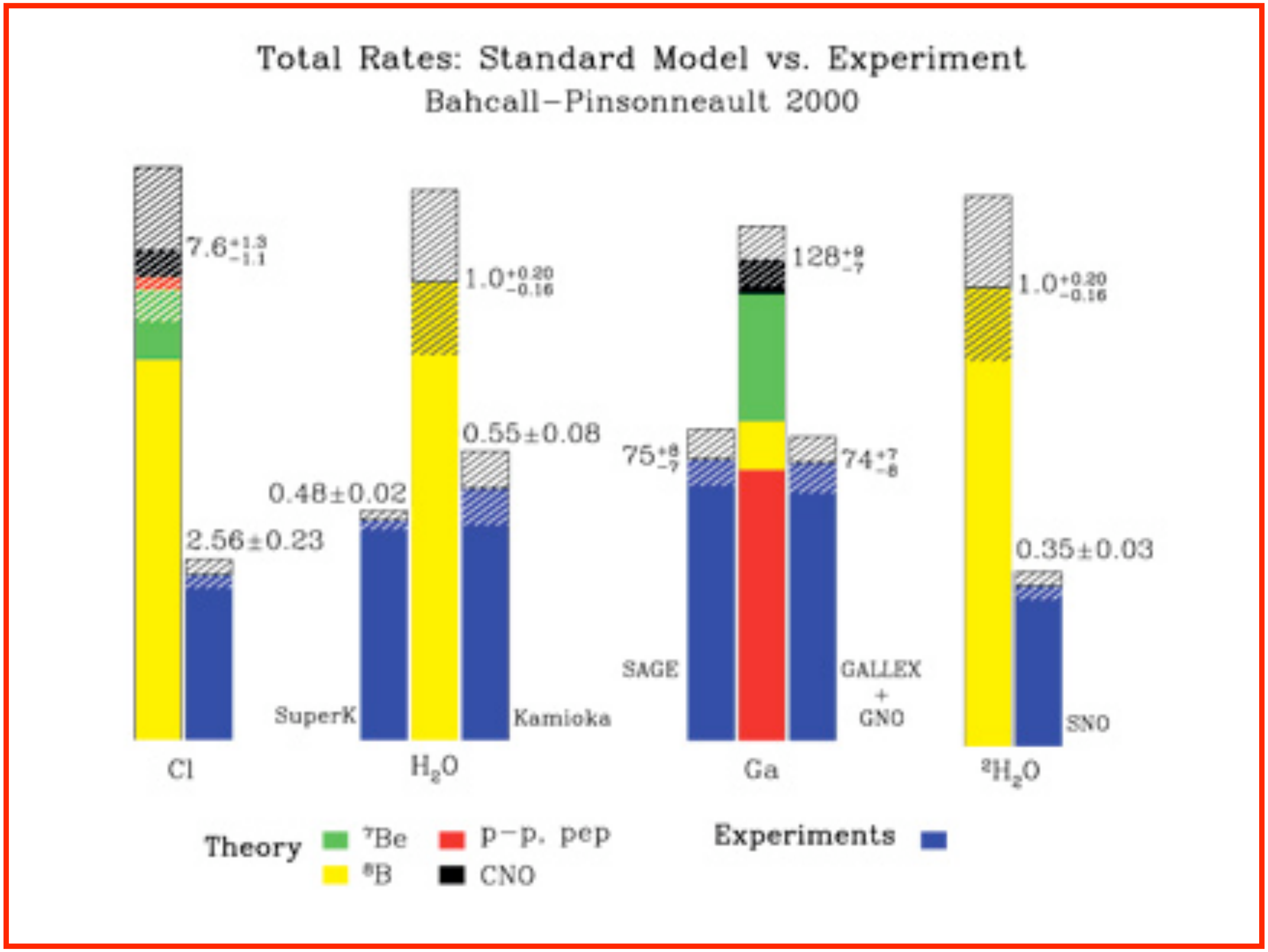


Solar Neutrinos

- Final solar issue. Neutrinos.
- Because they zoom straight from the center of the Sun where they are produced, neutrinos give us a picture of the center of the Sun.
- Even though they are hard to catch, seemed worthwhile to attempt to count the Solar neutrinos and verify the solar models.

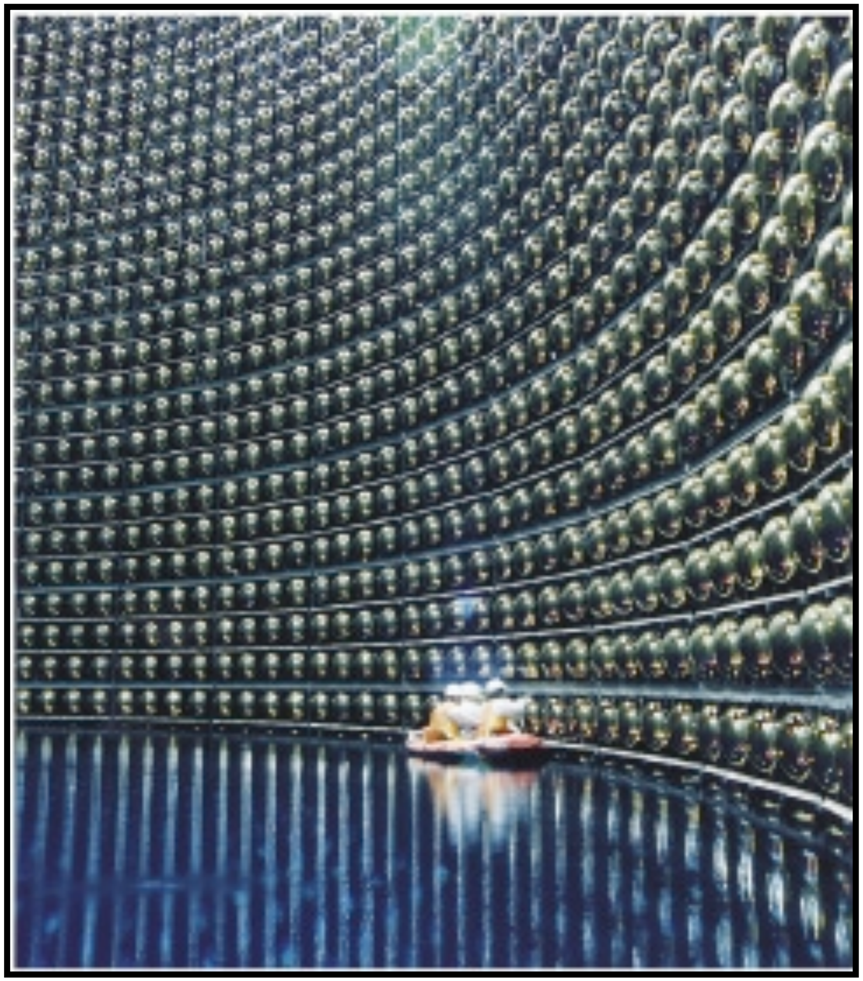
Solar Neutrinos

- In the 1960s an experiment was set up to count solar neutrinos -- 1 out of every 10^{16} neutrinos that flow through a tank with 100,000 gallons of cleaning fluid turned a chlorine atom into an argon atom. Started counting and they came up short by about a factor of three.
- This was the great <u>Solar Neutrino Problem</u>.



Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
7.6 +1.3 −1.1
2.56±0.23
1.0 +0.20 −0.16
0.48±0.02
0.55±0.08
SuperK
Kamioka
128 +9 −7
75 +8 −7
74 +7 −8
SAGE
GALLEX + GNO
1.0 +0.20 −0.16
0.35±0.03
SNO
Cl
H2O
Ga
2H2O
Theory
7Be
8B
p-p, pep
CNO
Experiments

Solar Neutrino Problem



- Additional experiments started up and the deficiency of solar neutrinos has been verified.
- This caused some consternation about our knowledge of the Sun, but has turned out to be a property of neutrinos and a triumph for astrophysics.

The Main Sequence

- Once the energy source of stars has been identified, it is easy to understand the main sequence in the H-R Diagram.

  (1) More massive stars require higher central temperatures (hydrostatic eqm.)

  (2) The P-P fusion rate and luminosity is proportional to T^4

Therefore, more massive stars will have higher central temperature and higher Luminosity. This is what is seen along the H-R Diagram main sequence.

Theoretical Main Sequence

- When you build careful models and try to quantitatively match the observed main sequence with P-P chain energy as a source it works very well for stars below $2M_o$.
- To explain the upper main sequence other versions of the P-P chain are required (and are well understood).

Philosophical Side Trip

- There is an interesting implication of our understanding of how the Sun and other stars produce energy:

The Universe is changing: H ->He

Stellar Lifetimes

- The Sun (and all stars) will eventually run out of fuel (hydrogen in regions where it is hot enough for fusion).
- If all the hydrogen in the Sun could fuse to helium, the Sun's lifetime would be 100 billion years.
- But, by the time about 10% of the Sun's H has been converted into He the solar structure will be changed and it will not be a main-sequence star.

Stellar Lifetimes

- The Sun has a main-sequence lifetime of 10 billion years. What about the other stars?

(1) The fuel for stars is mass

(2) The fuel consumption rate is Luminosity

So, it's easy!

$$\boxed{Life_{m-s} \propto \frac{Mass}{Luminosity}}$$

Example Stellar Lifetime

Suppose you have a $15M_o$ star with a luminosity of $L=10{,}000L_o$. How long will this star spend on the main sequence?

$$\boxed{Lifetime(15M_o) = \frac{15}{10000} \times Lifetime(1M_o)}$$

15 times as much fuel extends the life of the star

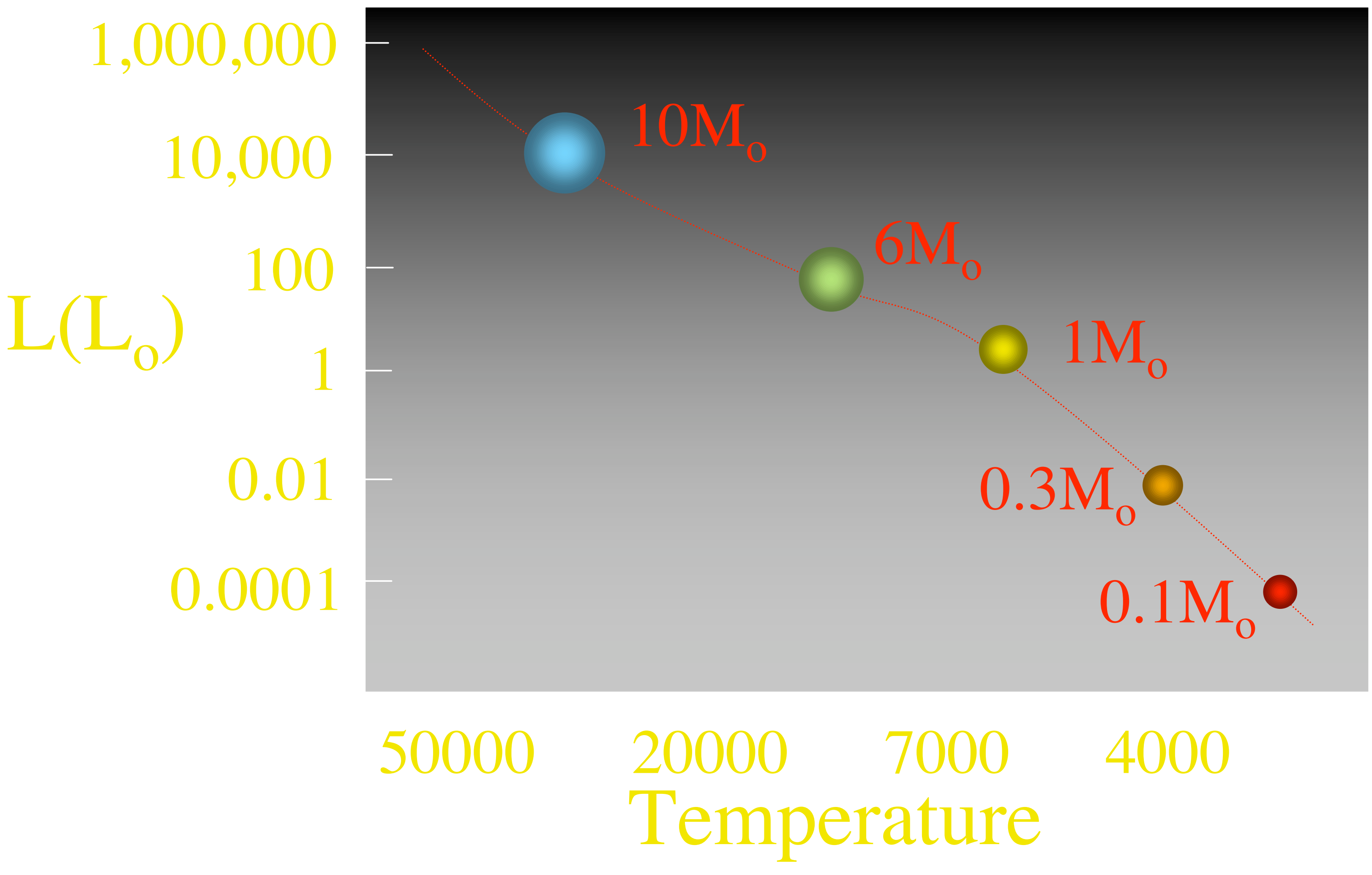
10,000 times L decreases the lifetime

Stellar Lifetimes

- So based on the extra fuel, you expect this star to live longer than the Sun, but this is more than counteracted by the high rate of using the fuel. This is the general trend.

Massive stars are like gas-guzzling SUVs
Low-mass stars are Toyota Prius.

Lifetimes can be read from a plot of Mass vs L



Stellar Lifetimes

- Remember there was a Mass-Luminosity relation for the main sequence. This gives the mass-lifetime relationship:

$$\boxed{\begin{aligned} &L \propto M^4 \\ &Lifetime \propto \frac{M}{L} = \frac{M}{M^4} = \frac{1}{M^3} \end{aligned}}$$

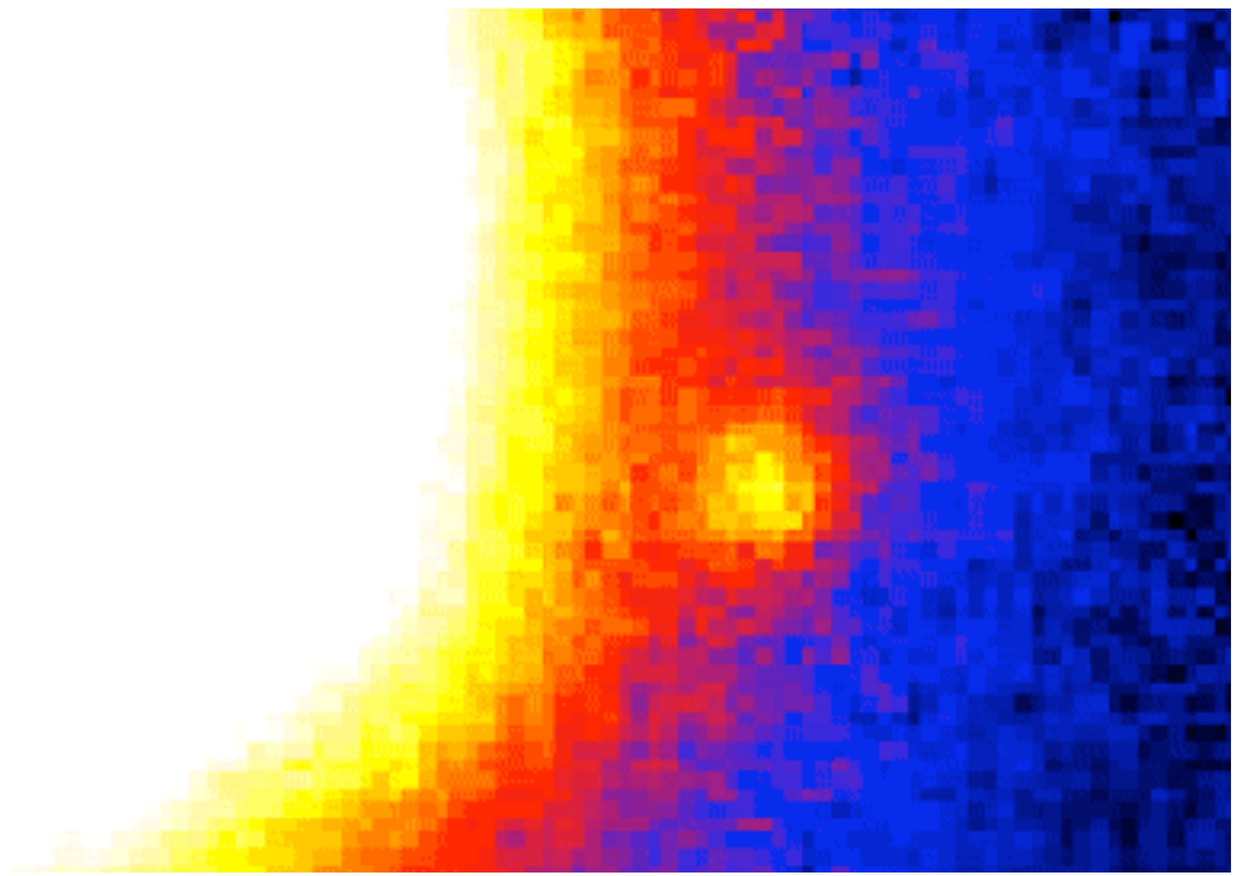
- Lifetimes range from a <u>few million</u> to <u>100 trillion years</u>.

Lower Mass Limit for Stars

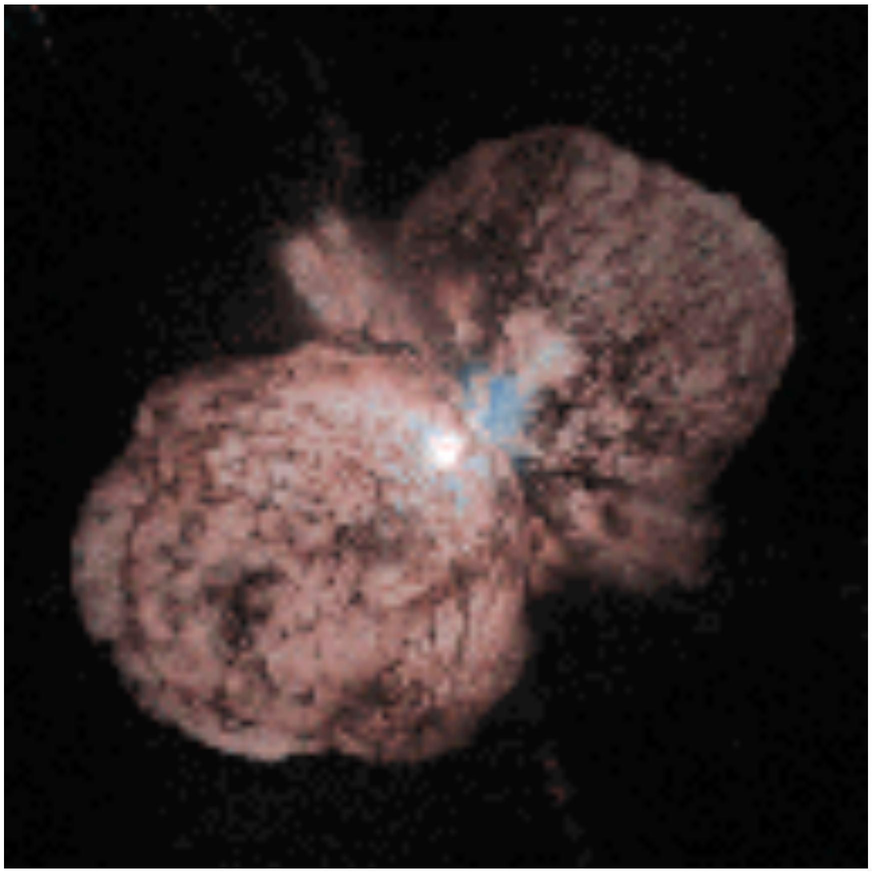
- We now can see why there is a <u>lower</u> limit for the mass of a star of about $0.08M_o$.
- For decreasing mass, the central temperature of a star decreases. At $0.08M_o$ the central temperature drops below 10 million k and it is too cool for P-P fusion!

- We call these objects `Brown Dwarfs'

GL229B (1995)



Upper Stellar Mass Limit



Eta Carina is a star of almost 100 solar masses.

Radiation pressure is blasting off the outer parts.