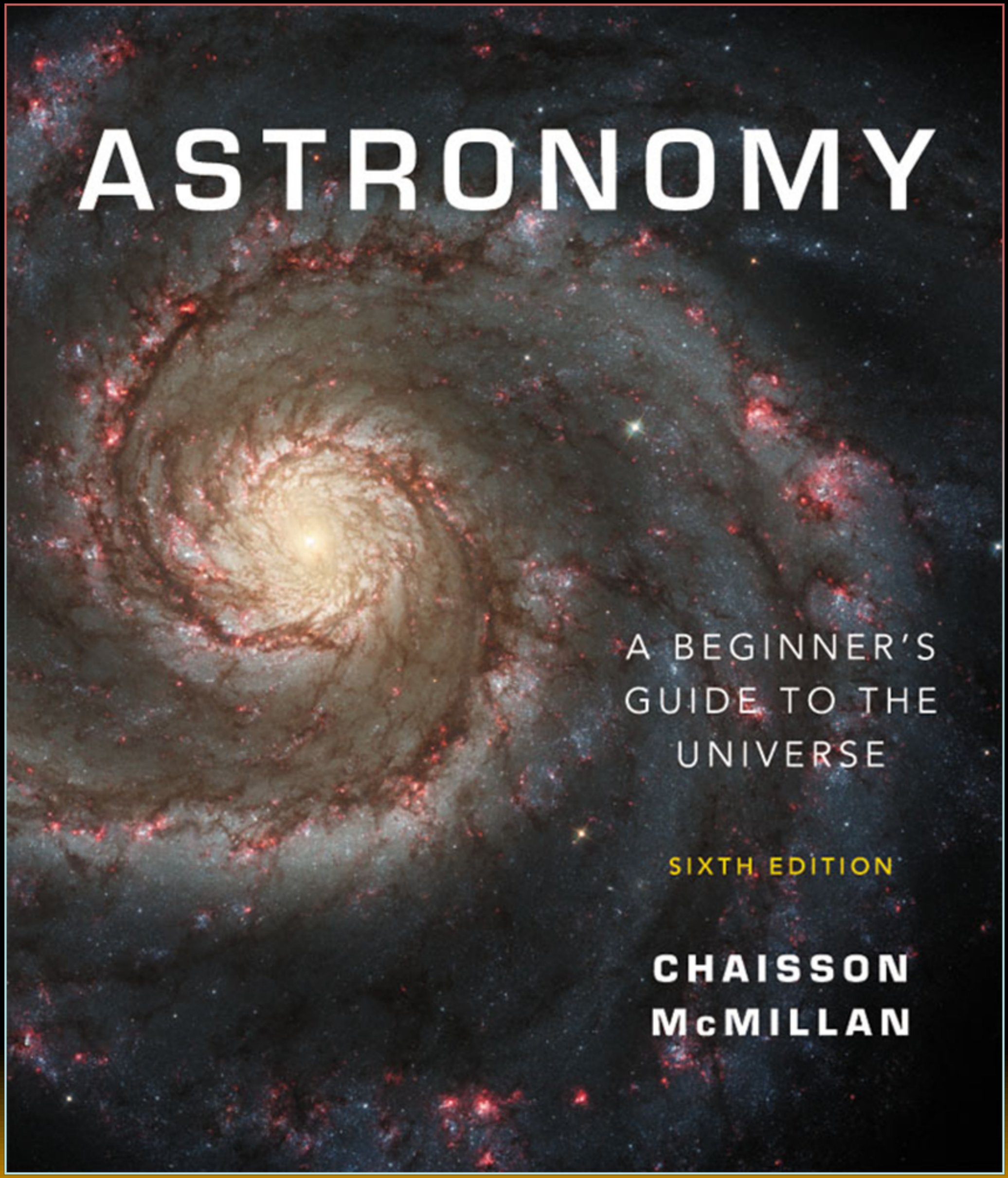


Chapter 9

The Sun

Our Parent Star

Prepared by R. Erickson

Nearly a trillion trillion stars inhabit our universe — the Sun is but one of these

Of these our Sun is an average star

300,000 times closer than the next nearest star, Alpha Centauri

Alpha Centauri is 4.3 light-years away (it takes that long for it’s light to travel to us)

The Sun is only 8 light-minutes away

Consequently, we know far more about the Sun than any of the distant points of light in the universe.

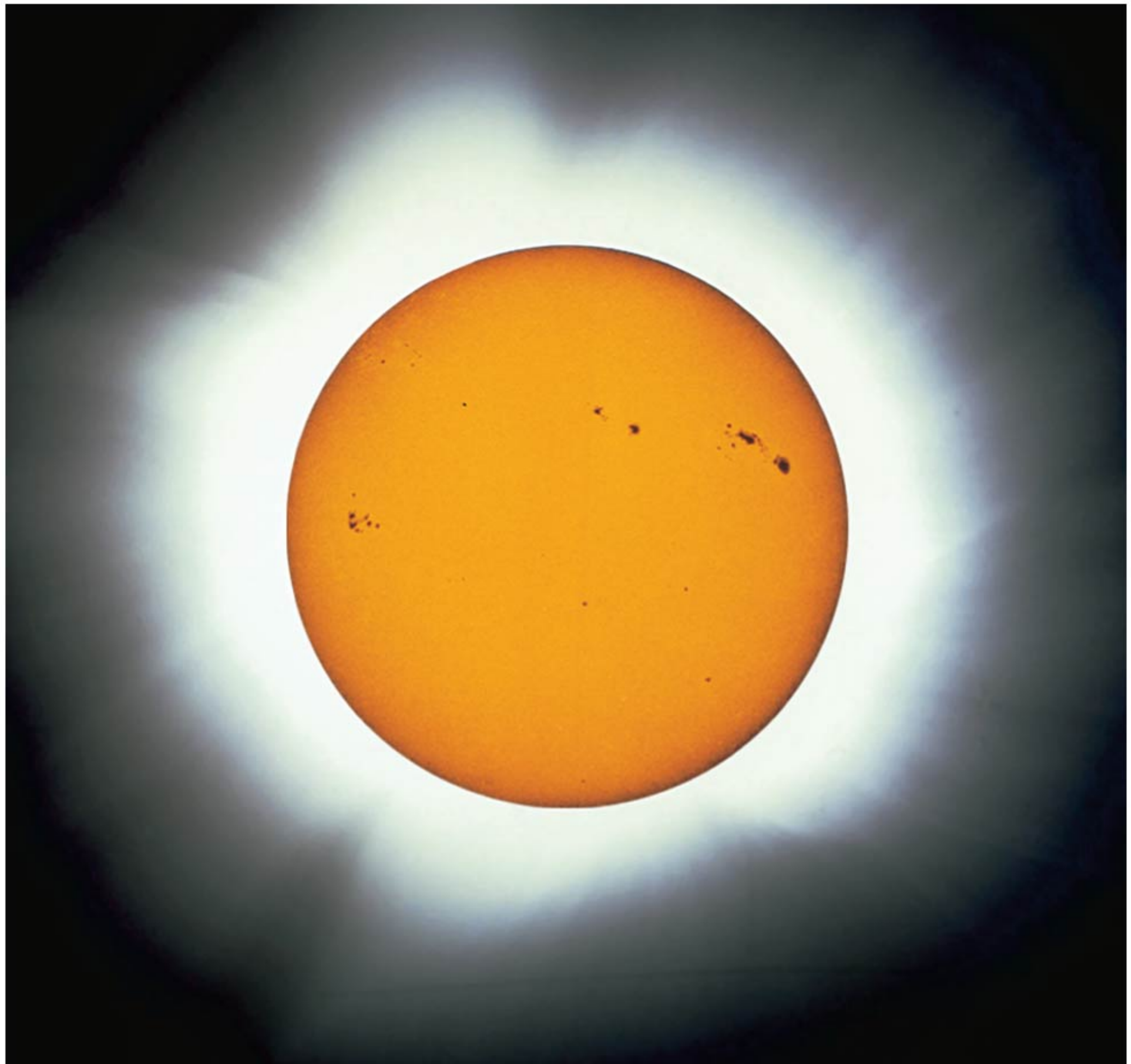
WARNING: The Sun is a brilliant ball of gas TOO BRIGHT to perceive with our eyes directly. We must view it through a heavy filter.

<u>The Solar Surface</u>:

The layer of the Sun that emits <u>most of the visible light</u> is called the photosphere.

This gaseous "surface" is no more than 500 km thick

Since the Sun's radius is 700,000 km - the photosphere is like a sheet of <u>tissue paper</u> wrapped around a large basketball.



The Solar Atmosphere: *Above* the photosphere —

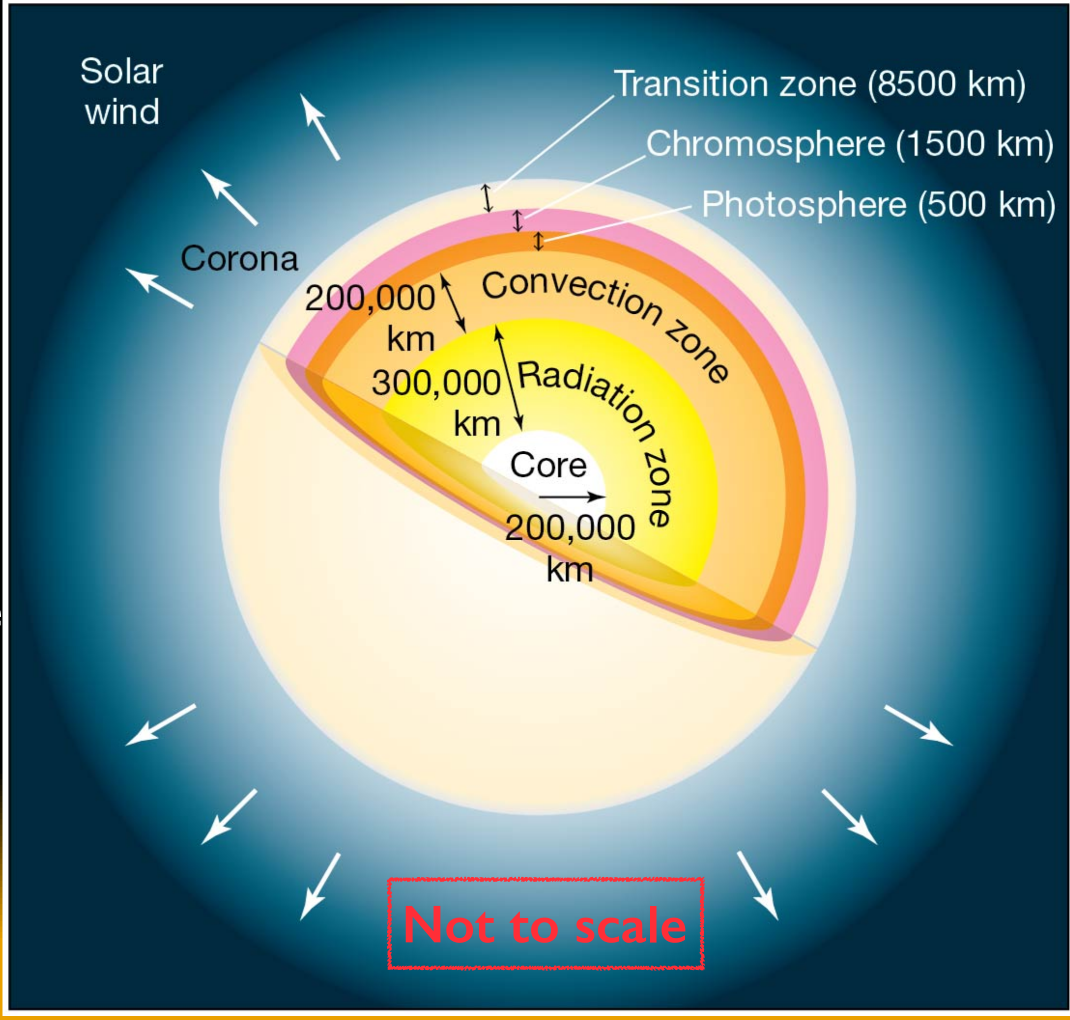
* The chromosphere (1500 km thick). It is the Sun's lower "atmosphere"
* The transition zone, (8500 km thick). Here the temperature rises dramatically
* The solar corona, a thin, *hot* upper atmosphere stretches far beyond the Sun
* Finally the solar wind, which flows away from the Sun and permeates the entire solar system

The Solar Interior: *Below* the photosphere —

* The convection zone, a region where the *material* of the Sun is in a constant convective motion

* The radiation zone, where solar *energy* is transported from the core toward the surface by radiation rather than by convection

* Finally comes the core where all the Sun's energy is generated.



Luminosity

The Sun's total energy output , called Luminosity, is *measured* in two steps:

Step I:

Measure energy on the Earth's surface using various techniques (Solar Panels, etc) *keeping in mind that only 50–70 percent* of the Sun's energy reaches Earth's surface; the rest is intercepted by the atmosphere (30 percent) *or* reflected away by clouds (0–20 percent).

So we must extrapolate surface energy to upper atmosphere energy.

The energy hitting the top of our atmosphere, is called the solar constant. It is approximately 1400 watts per square meter (14 one-hundred watt light bulbs of heat).

A sunbather's body has a total surface area of about 1/2 m^2 and receives solar energy at a rate of roughly 500 watts (five 100-W lightbulbs)

Luminosity

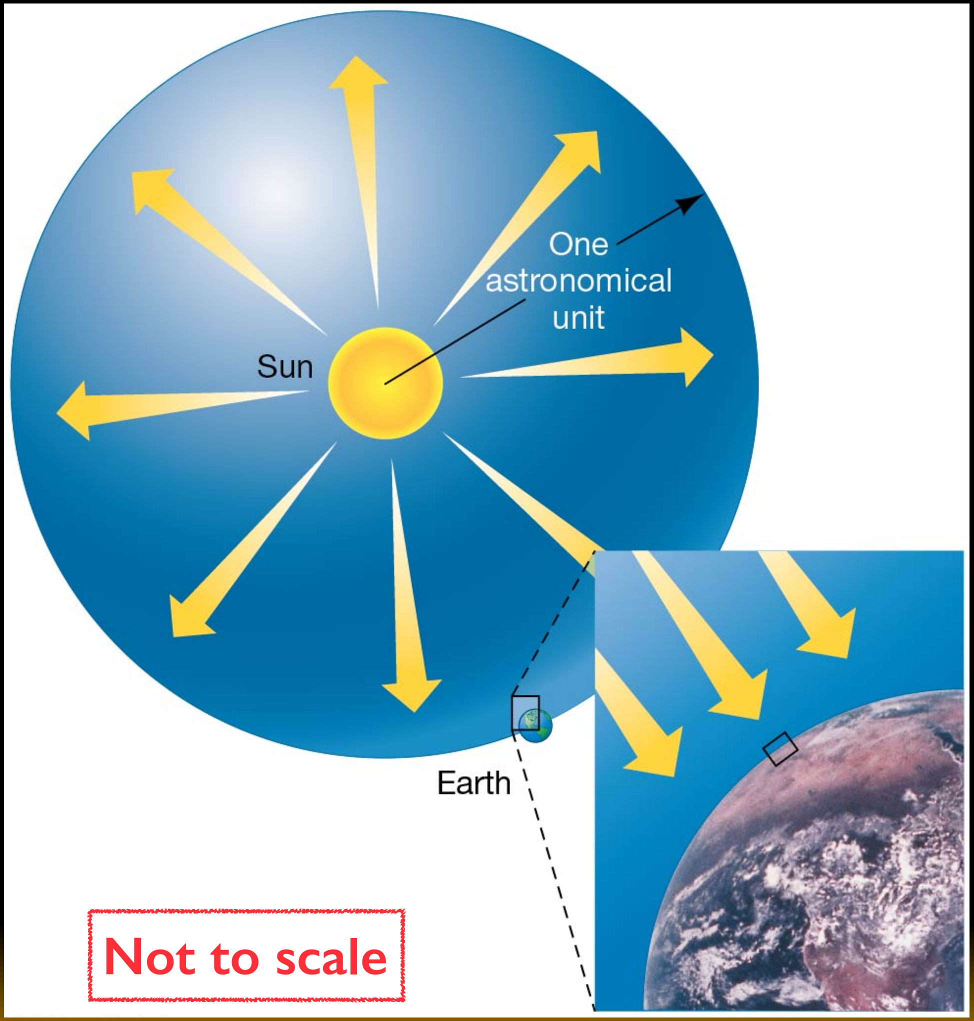
Step II:

Find the TOTAL surface area of a *sphere* 1 AU out from the Sun, which is 2.8×10^{23} m^2 using

$$A = 4\pi r^2$$

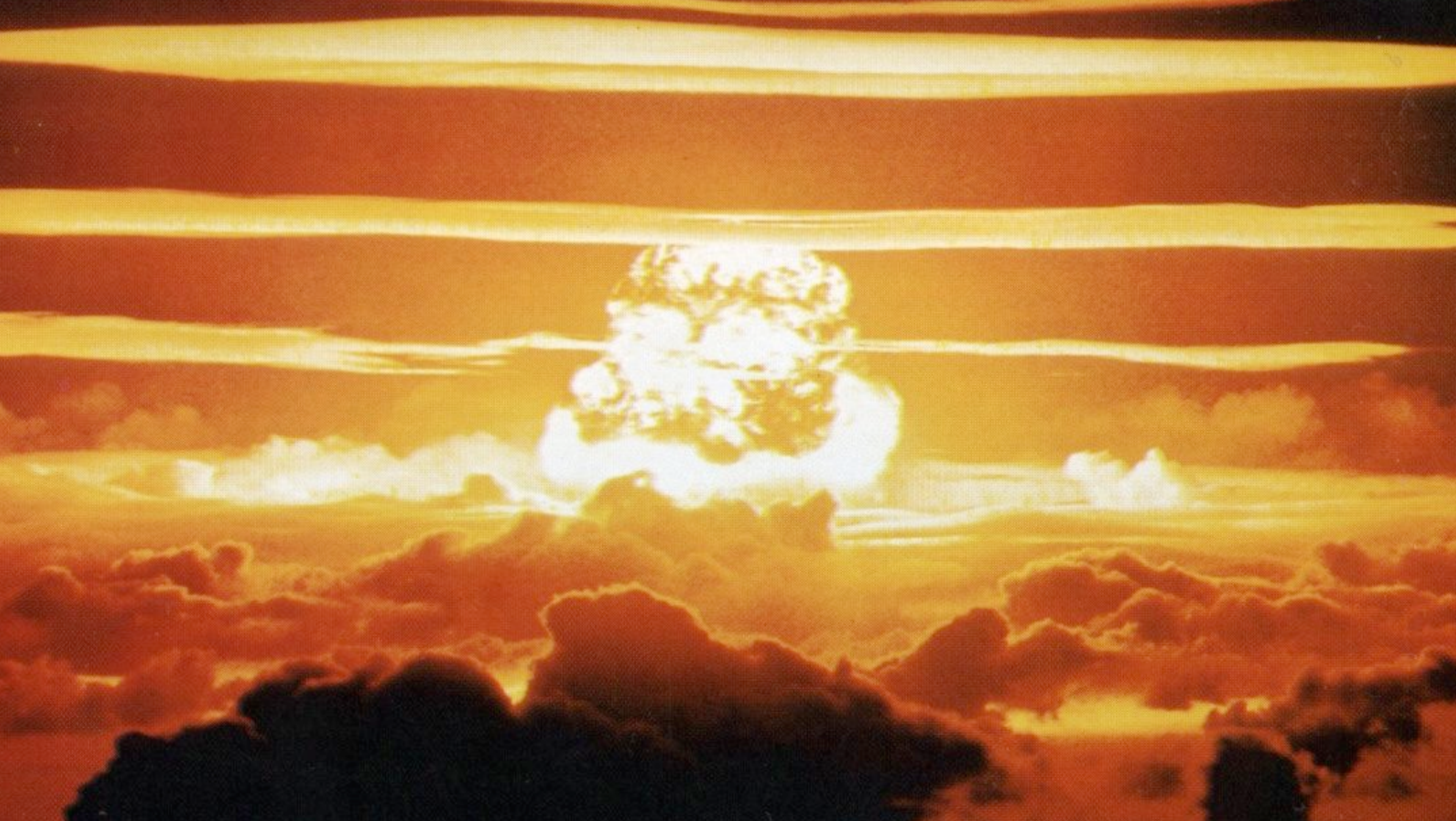
Then, multiply the total surface area by the solar constant, yielding the energy passing across our 1 AU sphere: 4×10^{26} Watts

The Conservation of Energy dictates that the total energy leaving the Sun's surface is the same: 4×10^{26} Watts



Luminosity

The Sun produces energy equivalent to 100 billion 1-megaton nuclear bombs going off *every second*



The Standard Solar Model

Astrophysicists create mathematical models of the Sun combining all observations and theoretical insight into solar physics

The resulting model is called the standard solar model and has gained widespread acceptance

BTW: We construct *similar models* for other types of stars (Chpt 11/12)

Because the Sun is so close and well studied, the standard solar model is by far the best tested solar model created

Equation of Hydrostatic Equilibrium	$\frac{dP}{dr} = -\rho \frac{GM_r}{r^2}$
Equation of Mass	$\frac{dM_r}{dr} = 4\pi r^2 \rho$
Equation of Energy Conservation	$\frac{dL_r}{dr} = 4\pi r^2 \rho \varepsilon$
Equation of Radiative Transport	$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L_r}{4\pi r^2}$ (radiative)
Equation of Convective Transport	$\frac{dT}{dr} = \left(1 - \frac{1}{\gamma}\right)\frac{T}{P}\frac{dP}{dr}$ (convective)
Equation of State	$P = P(\rho, T, X, Y)$
Equation of Opacity	$\kappa = \kappa(\rho, T, X, Y)$
Equation of Energy Generation	$\varepsilon = \varepsilon(\rho, T, X, Y)$

where r is a running variable representing the radius from the center of the star,

P = Pressure at r,

T = Temperature at r,

M(r) = Mass within the sphere with the radius r,

L(r) = Energy flux through the sphere with radius r,

X = Fraction of hydrogen by weight,

Y = Fraction of helium by weight,

a = Stefan-Boltzmann constant,

c = Velocity of light,

G = Gravitational constant,

rho is the density, and gamma is the ratio of the specific heats cp/cv.

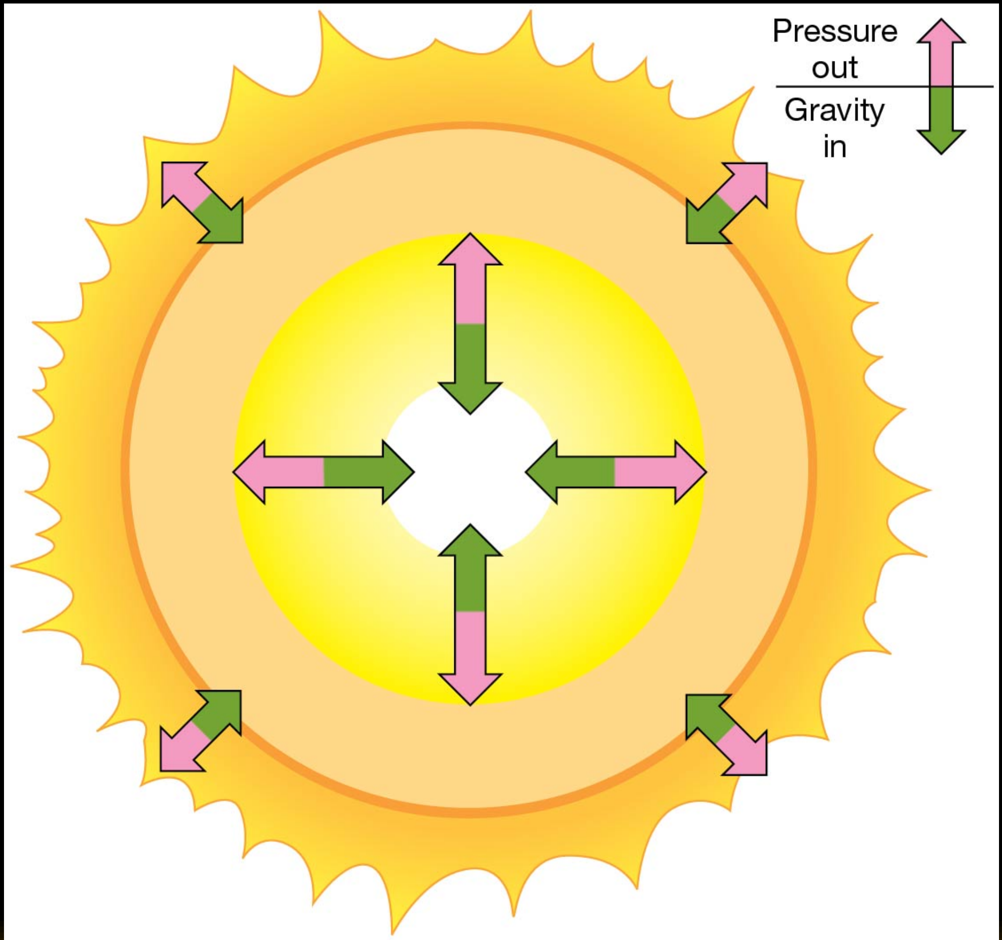
The Standard Solar Model

Sun is in a state of hydrostatic equilibrium, in which pressure's outward push *exactly* counteracts gravity's inward pull.

This balance explains why the Sun neither collapses under its own weight nor explodes into space.

This fact lets us *establish* the density and temperature inside the Sun.

In turn, we can model and predict other solar properties — luminosity, radius, spectrum, and so on.



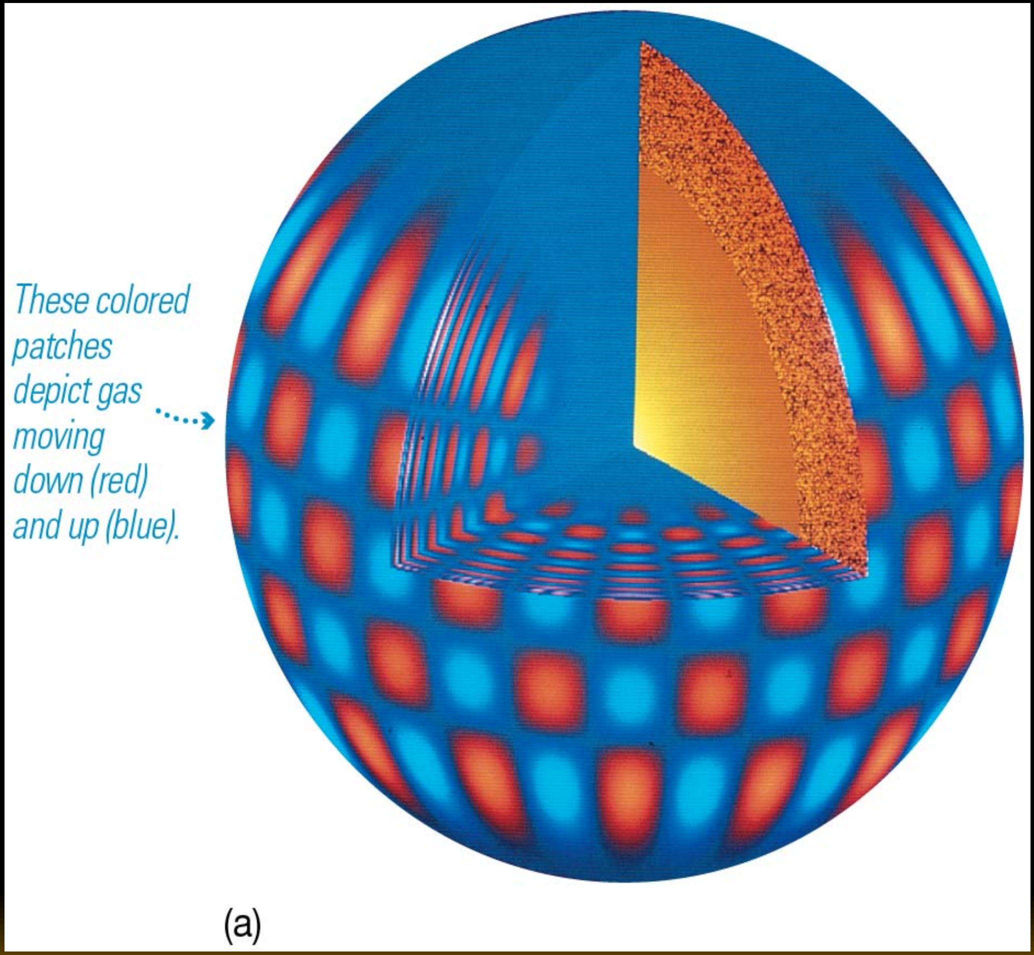
The Standard Solar Model

An example: In the 1960s, measurements of Doppler shifts of solar spectral lines revealed that the surface of the Sun *oscillates* like a complex set of bells

These vibrations are the result of internal pressure waves ("sound") that reflect off the photosphere and *repeatedly* cross the solar interior

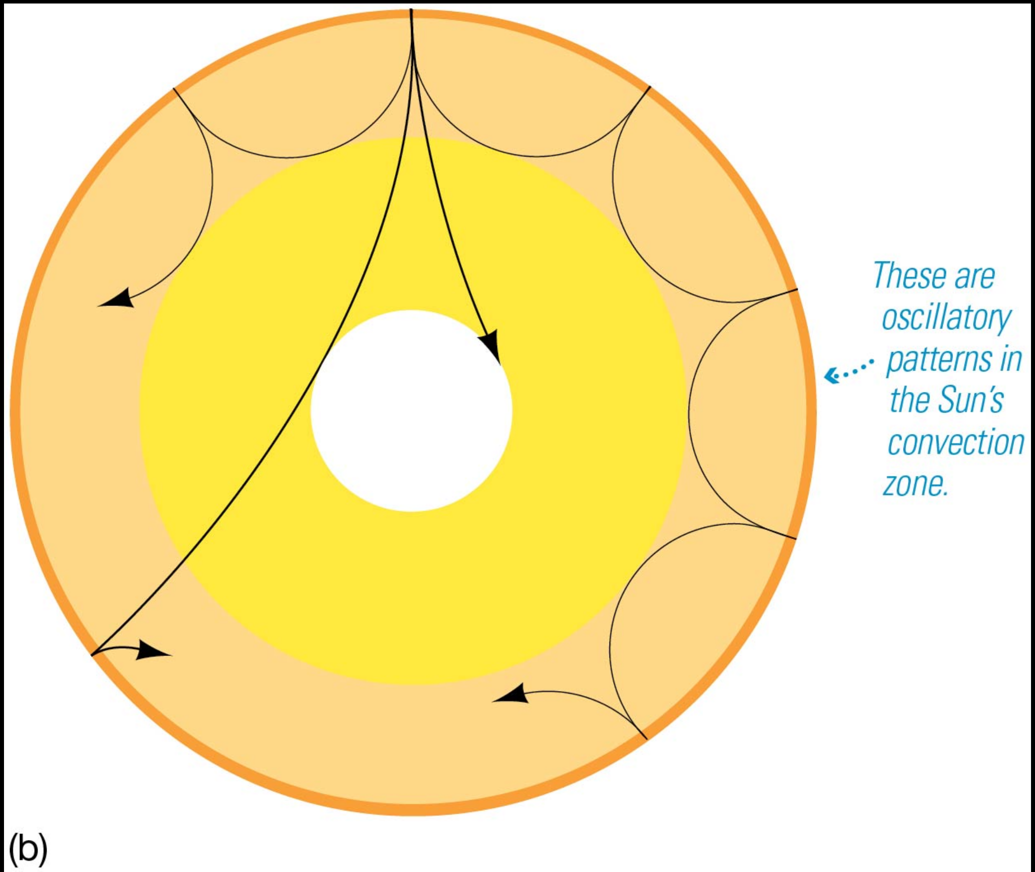
These waves penetrate deep inside the Sun

Analysis of surface patterns allows scientists to determine conditions far below the Sun's surface.



The Standard Solar Model

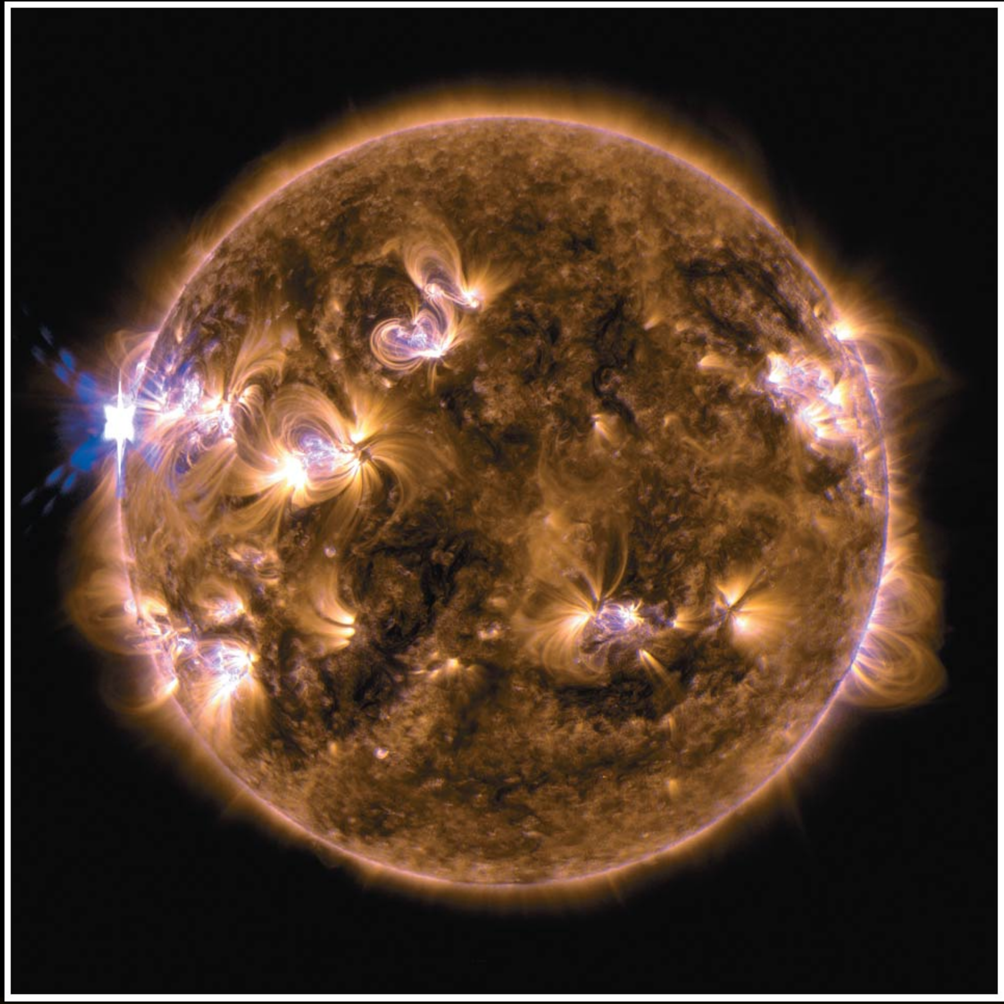
The agreement between the standard solar model and observations is spectacular - the frequencies and wavelengths of observed solar oscillations are within 1/10 of one percent of the model predictions.



Solar and Heliospheric Observatory

The space-based Solar and Heliospheric Observatory (SOHO) has provided *continuous monitoring* of the Sun's surface and atmosphere since 1995.

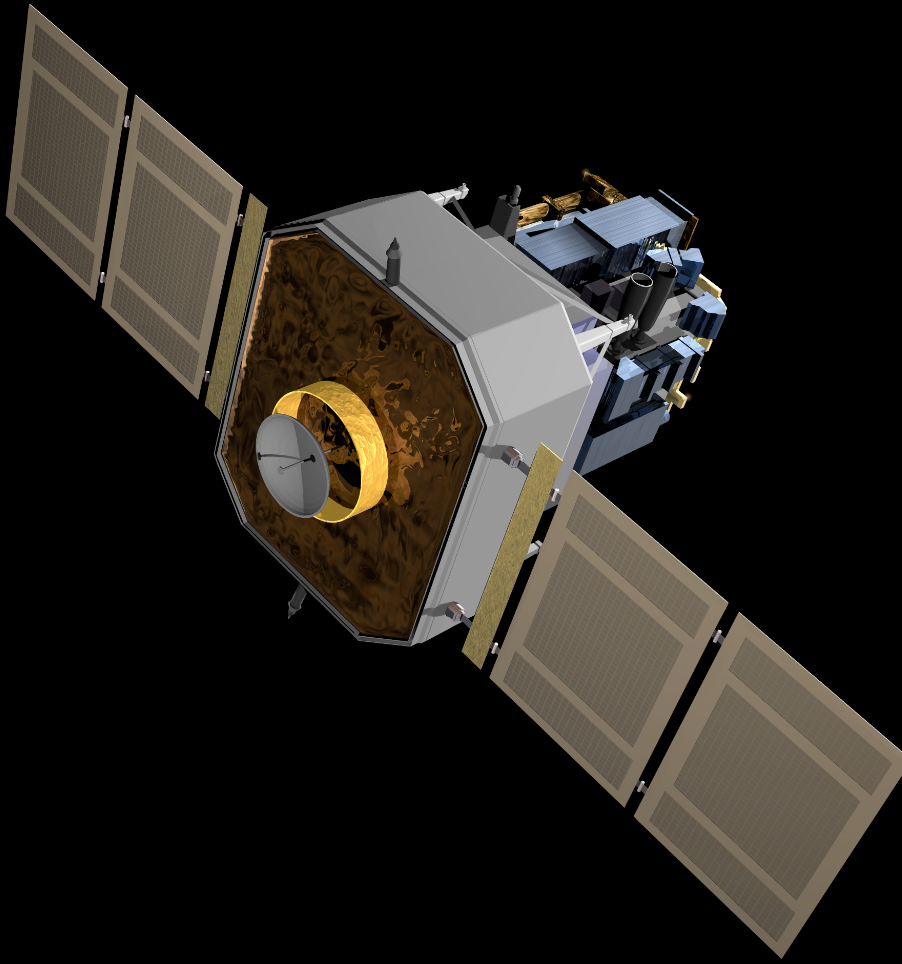
Data analysis provides detailed information about the temperature, density, rotation, and convective state of the solar interior, allowing direct *comparison with theory*



Solar and Heliospheric Observatory

SOHO is a billion-dollar mission operated primarily by the European Space Agency (ESA)

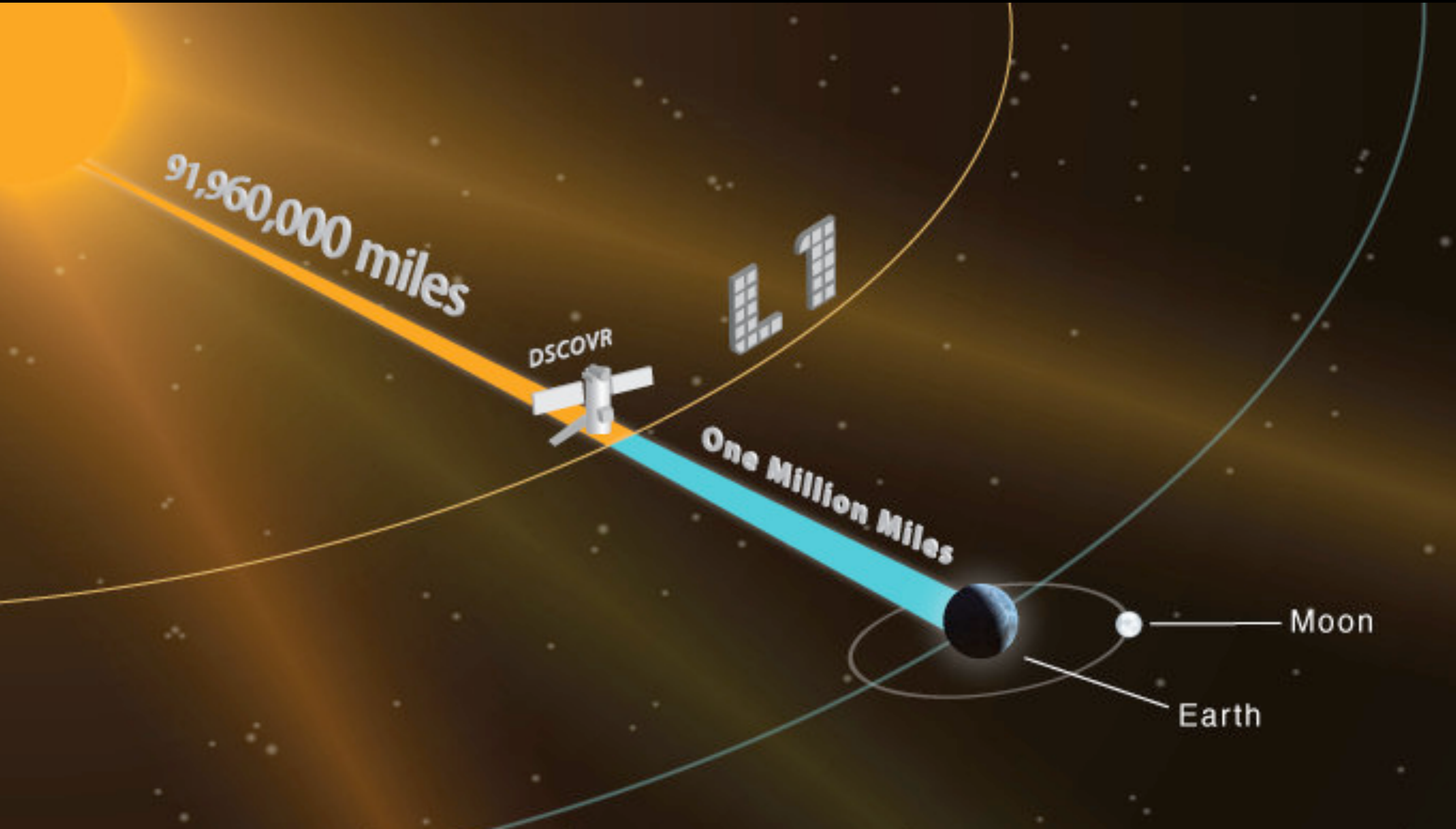
The 2-ton robot is on-station about 1.5 million km sunward of Earth - about 1 percent of the distance from Earth to the Sun.



Scott Manley: https://www.youtube.com/watch?v=k06c_87A74o

Solar and Heliospheric Observatory

The L1 Lagrangian point is the place where the gravitational pull of the Sun and Earth are precisely equal



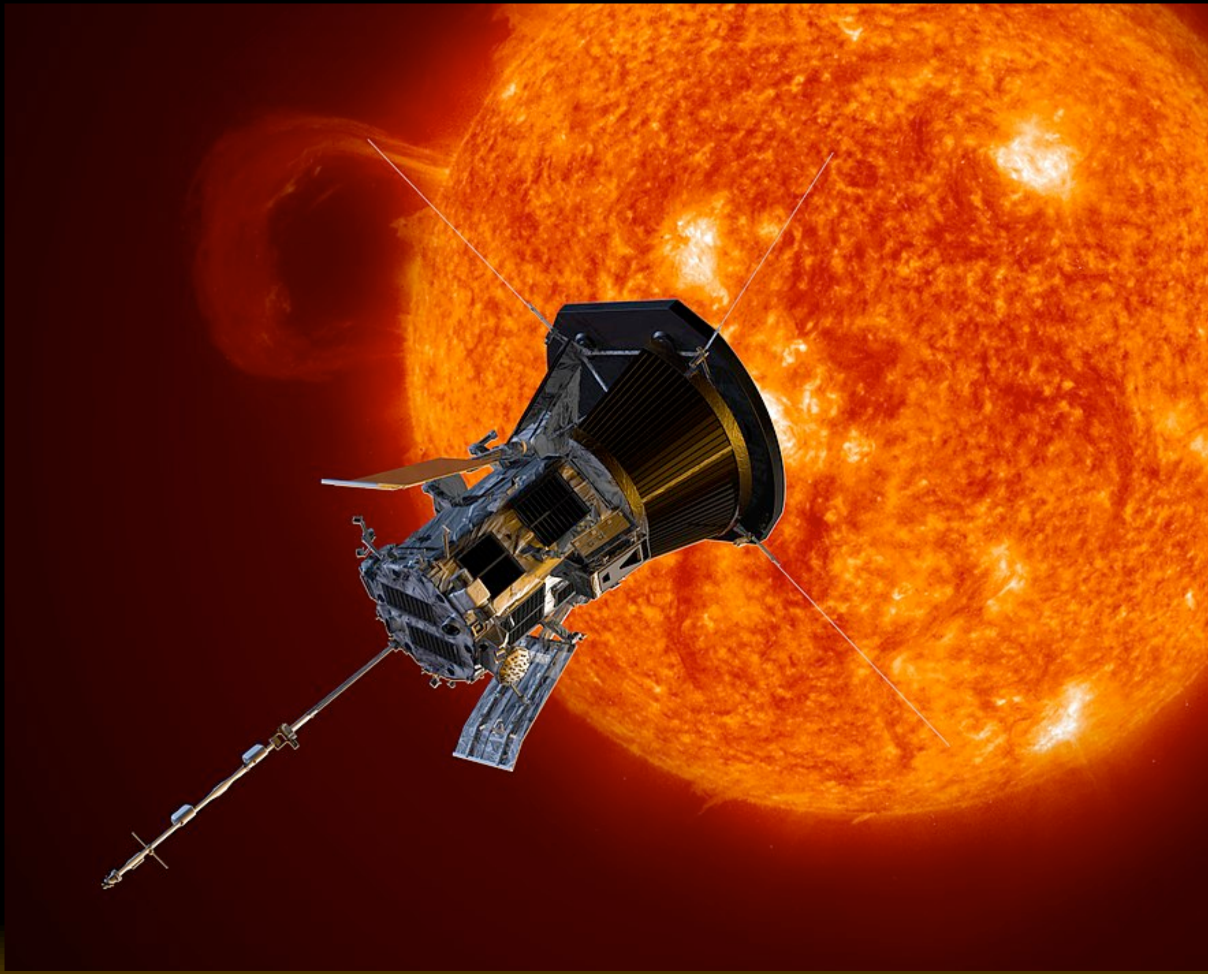
Parker Solar Probe

NASA's Parker Probe, launched in August of 2018, will make many firsts in space exploration over the course of seven years.

It will fly-by Venus seven times

As it passes through the sun's corona, it will become the fastest man-made object - as fast as 700,000 km/h (430,000 mph)

It will become the closest man-made object to our nearest star



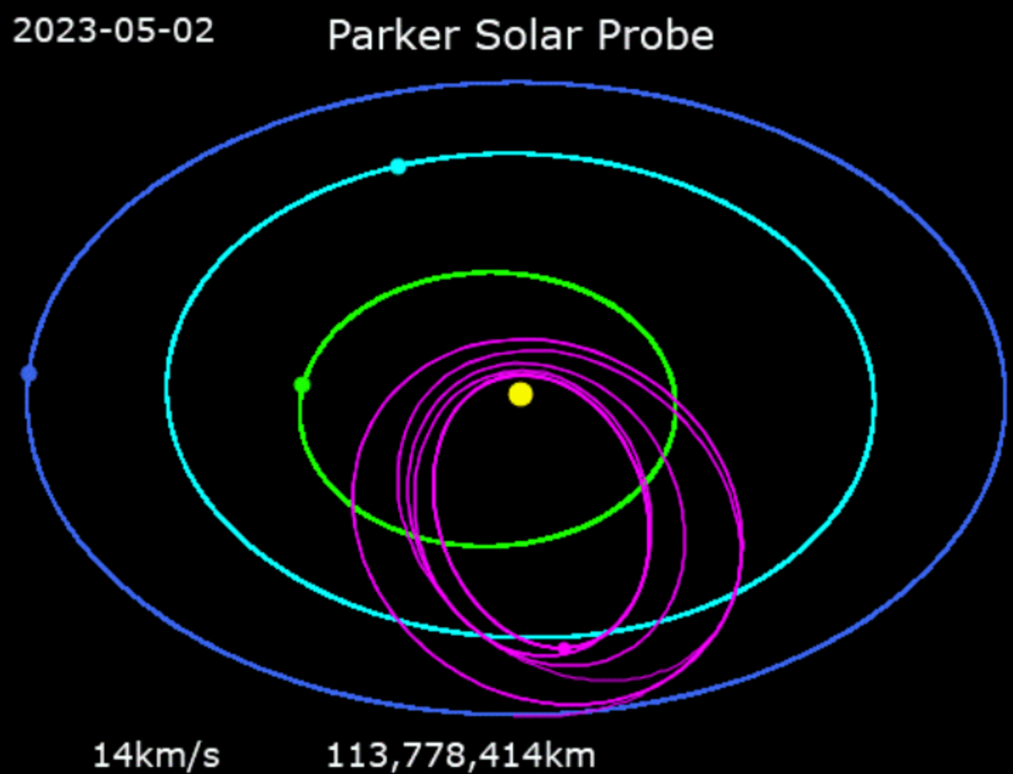
Summary: https://uncrate.com/video/how-nasas-parker-probe-will-touch-the-sun/

Parker Solar Probe

The Parker Probe's heat shields will partially ablate (disintegrate) as it moves through the corona, and its instruments will operate at room temperature

It seeks to solve the mystery behind why the corona is hotter than the surface of the sun.

The data is years away, but the Park Probe is poised to help us better understand the life-giving body so close to home.



Perihelion and aphelion are the nearest and farthest points, respectively, of a body in orbit around the Sun

https://en.wikipedia.org/wiki/Parker_Solar_Probe

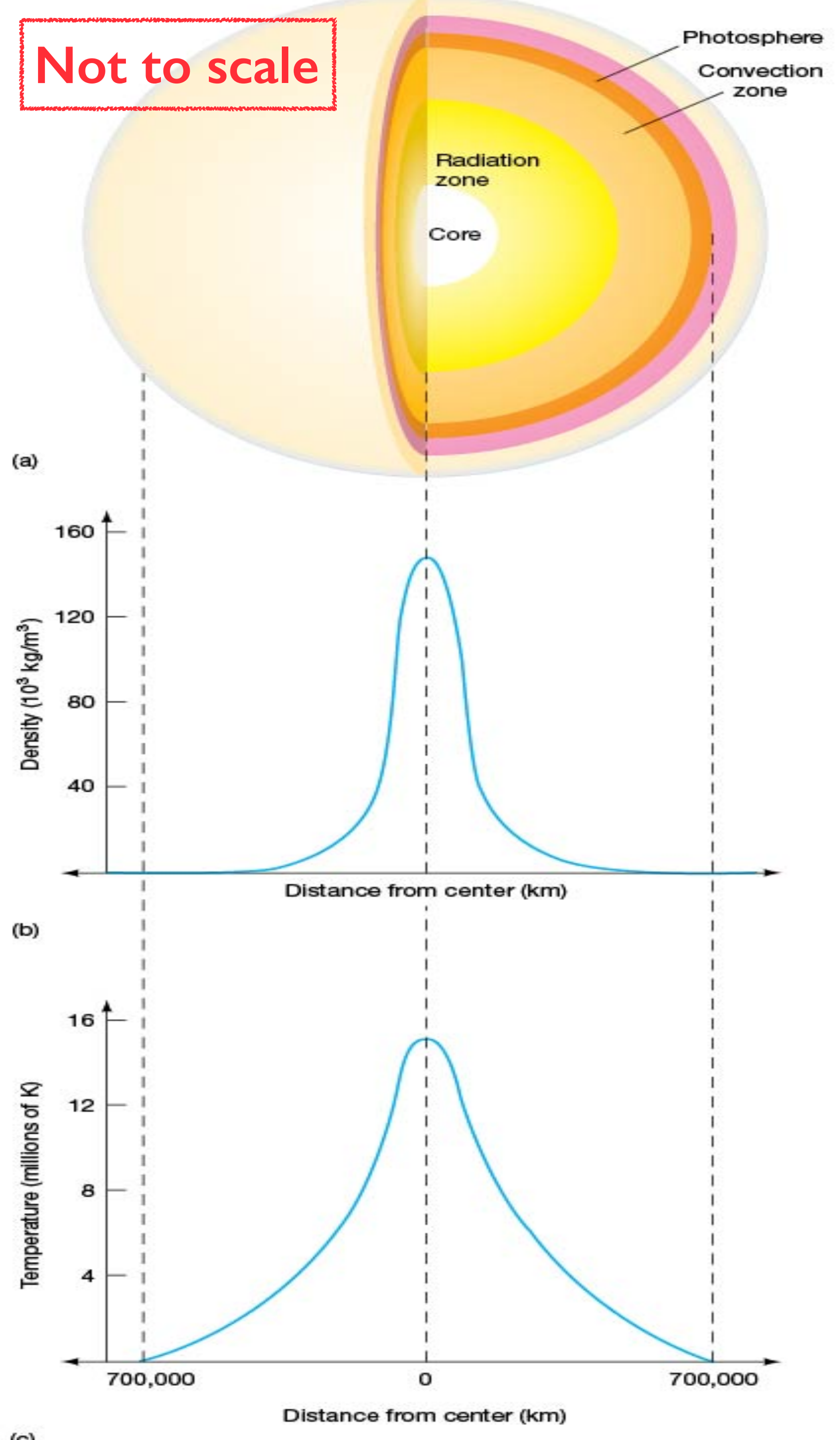
Tour at launch pad of the Delta IV that launched Parker (min 17): https://www.youtube.com/watch?v=x-vXJL8jXBk
Tour of Factory that builds the Delta IV rocket (min 25): https://www.youtube.com/watch?v=o0fG_lnVhHw

The Standard Solar Model
Temperature and Density

The Sun's density varies from 150,000 kg/m³, 20 times more dense than iron, to 0.0002 kg/m³, about 10,000 times *less dense* than air.

The *average* density of the Sun (if its volume is filled with a substance of constant density) is 1400 kg/m³ like that of Jupiter (which, in another life, may have been the Sun's binary had it been 80 times larger)

The temperature at the CORE is 15 million K and decreases steadily to the observed value of 5800 K at the photosphere.

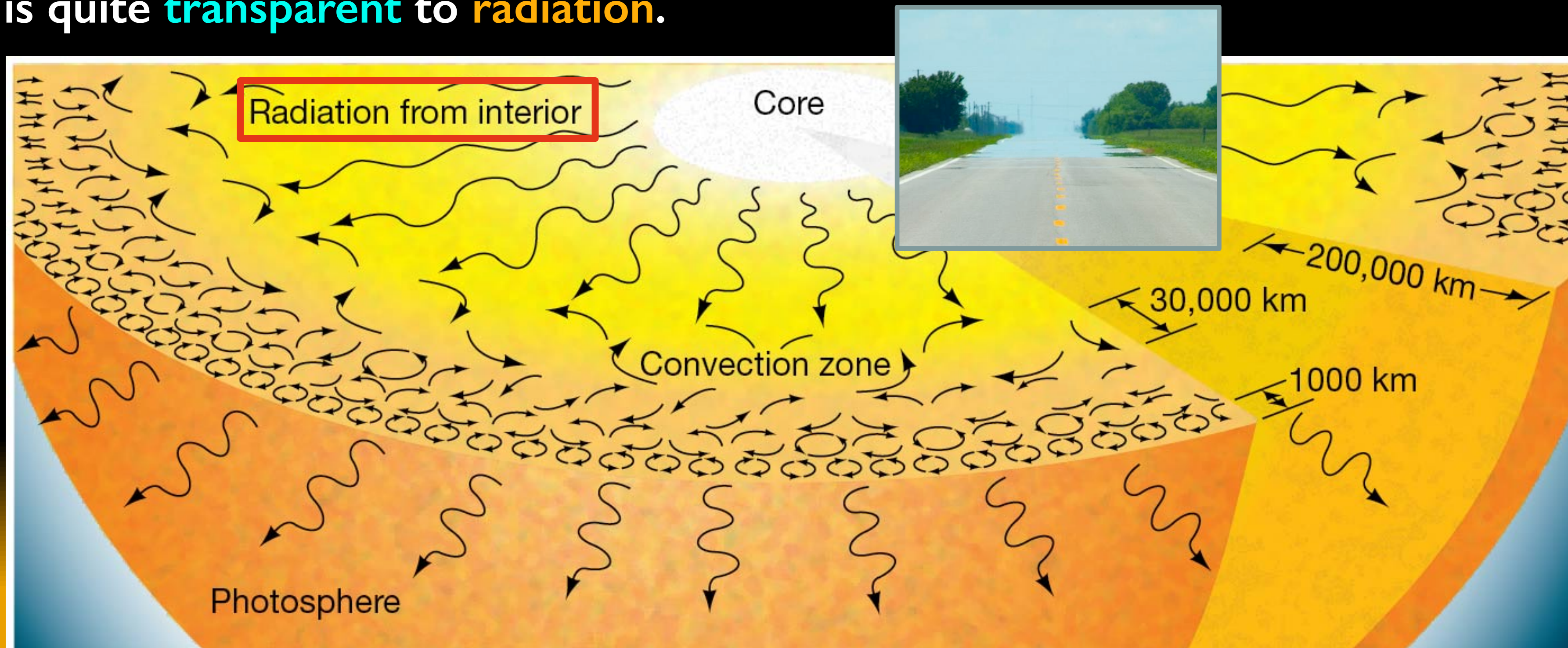


Radiation Zone

Energy produced by nuclear reactions in the CORE travels outward with relative ease in the form of electromagnetic radiation (in packets called photons)

Above the CORE the very hot solar interior ensures violent and frequent collisions among gas particles, completely ionizing atoms (electrons are stripped away).

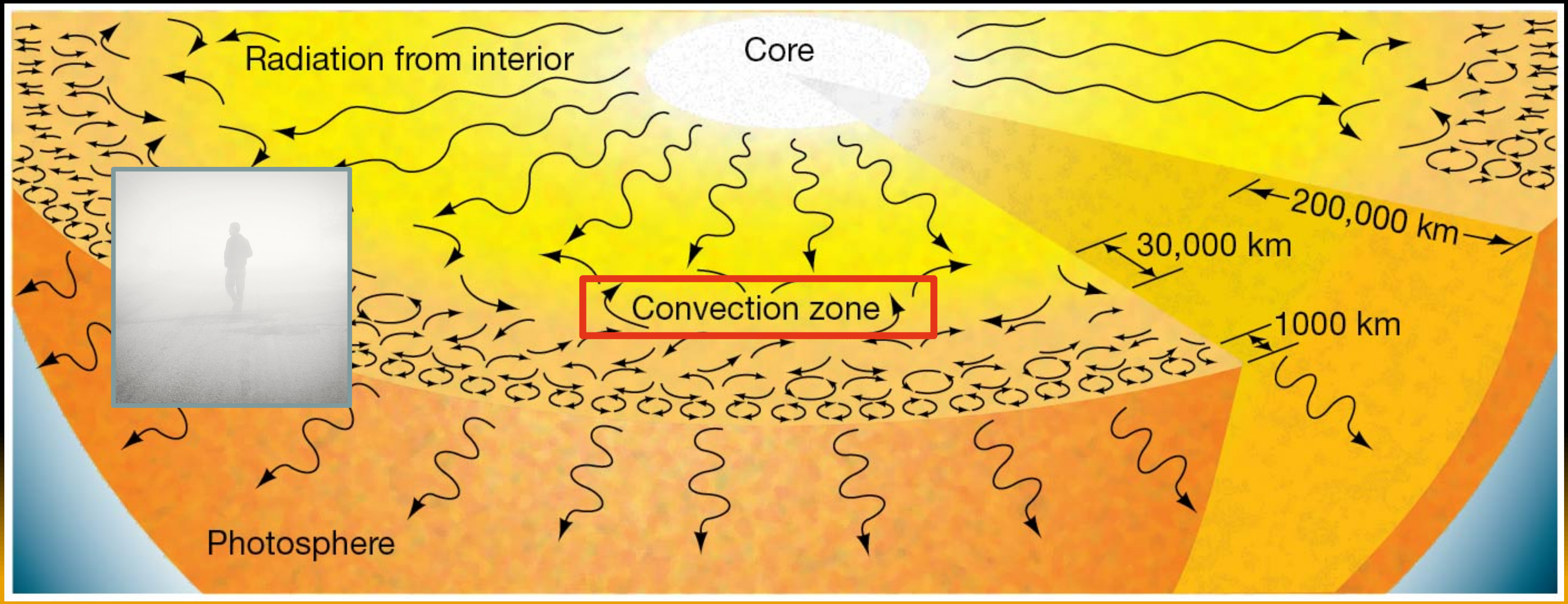
With <u>no electrons left on atoms</u> to capture photons, the deep solar interior is quite transparent to radiation.



Convection Zone

At the deepest tier, 200,000 km below the photosphere, the cells are tens of thousands of kilometers in diameter.

Energy is transported upward through a series of progressively smaller cells, stacked one upon another



Convection Zone

At the outer edge of the radiation zone (500,000 km from the center) the temperatures has fallen off, due in part to there being more volume to allow them to move around and thus fewer collisions occur.

Electrons can start to bind to atomic nuclei and the resulting atoms start absorbing this outbound radiation

This gas becomes almost totally opaque
(can't see through it - foggy like).

All of the photons produced in the Sun's core are absorbed. Not one of them reaches the surface. But what happens to the energy they carry?

We see the light from the Sun so we know energy in fact escapes.

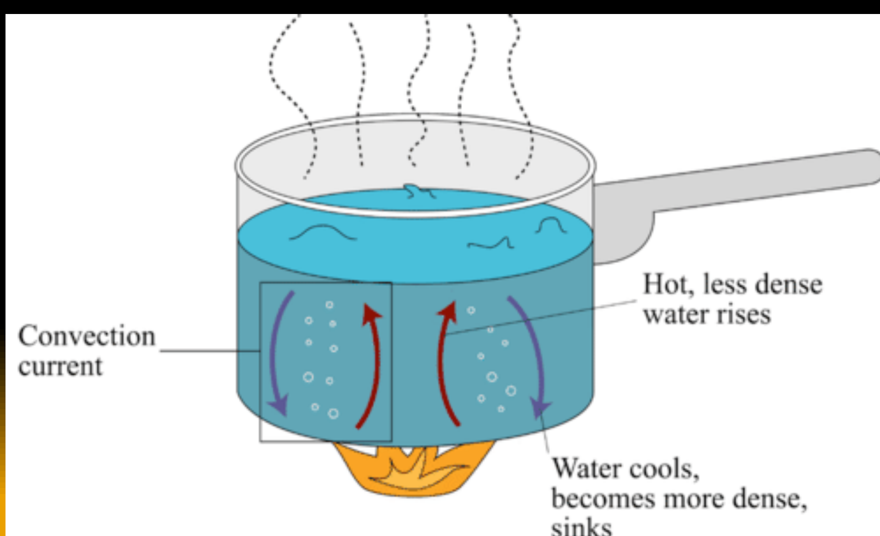
Q: How then is energy carried past the Radiation Zone?

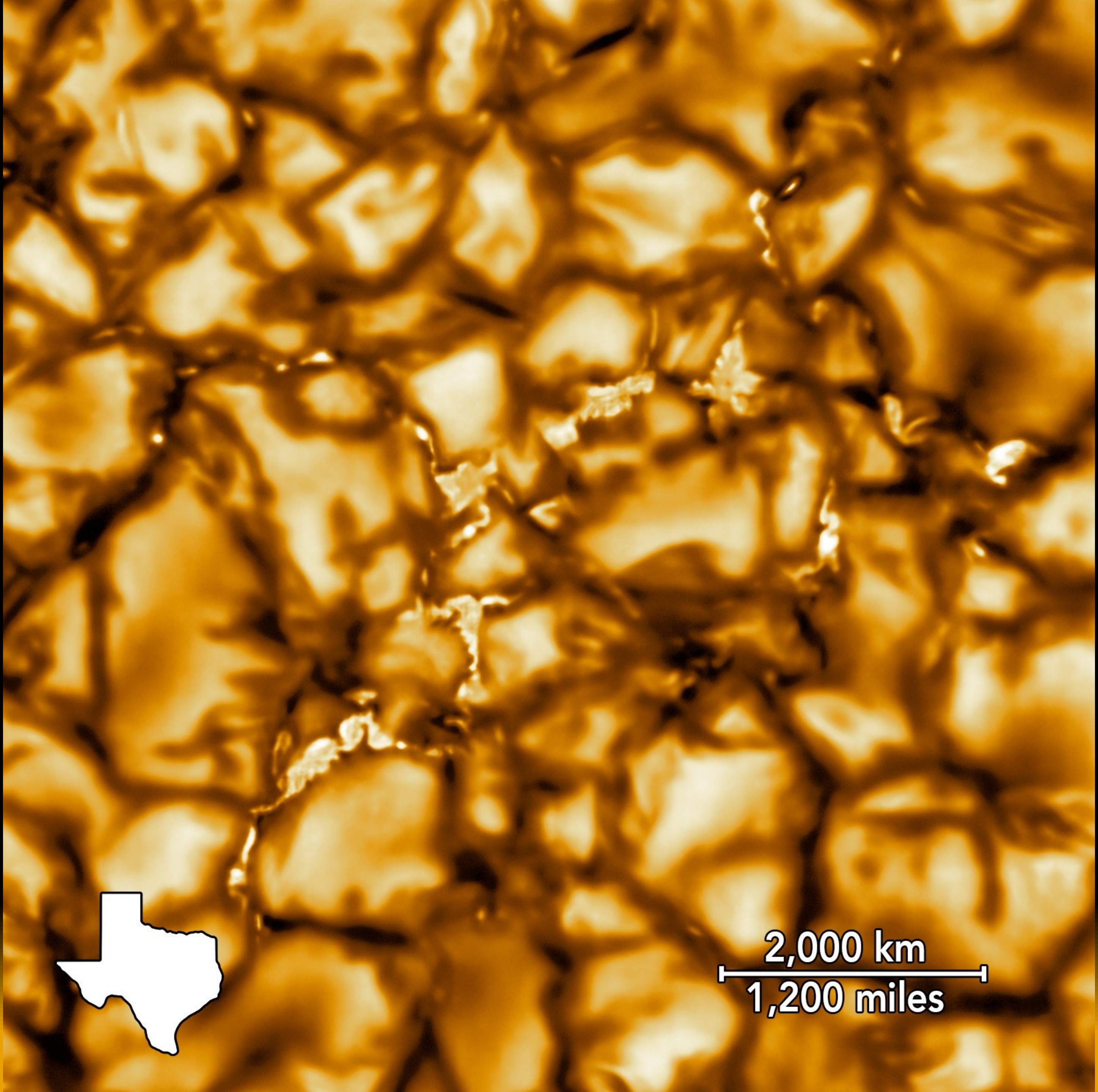
Convection Zone

A: Convection! - the same physical process we saw in our study of Earth's atmosphere.

Energy is transported to the surface by physical motion of the solar gas, like a boiling cauldron of tomato soup.

There are layer upon layer of convection cells in the convection zone.




2,000 km
1,200 miles

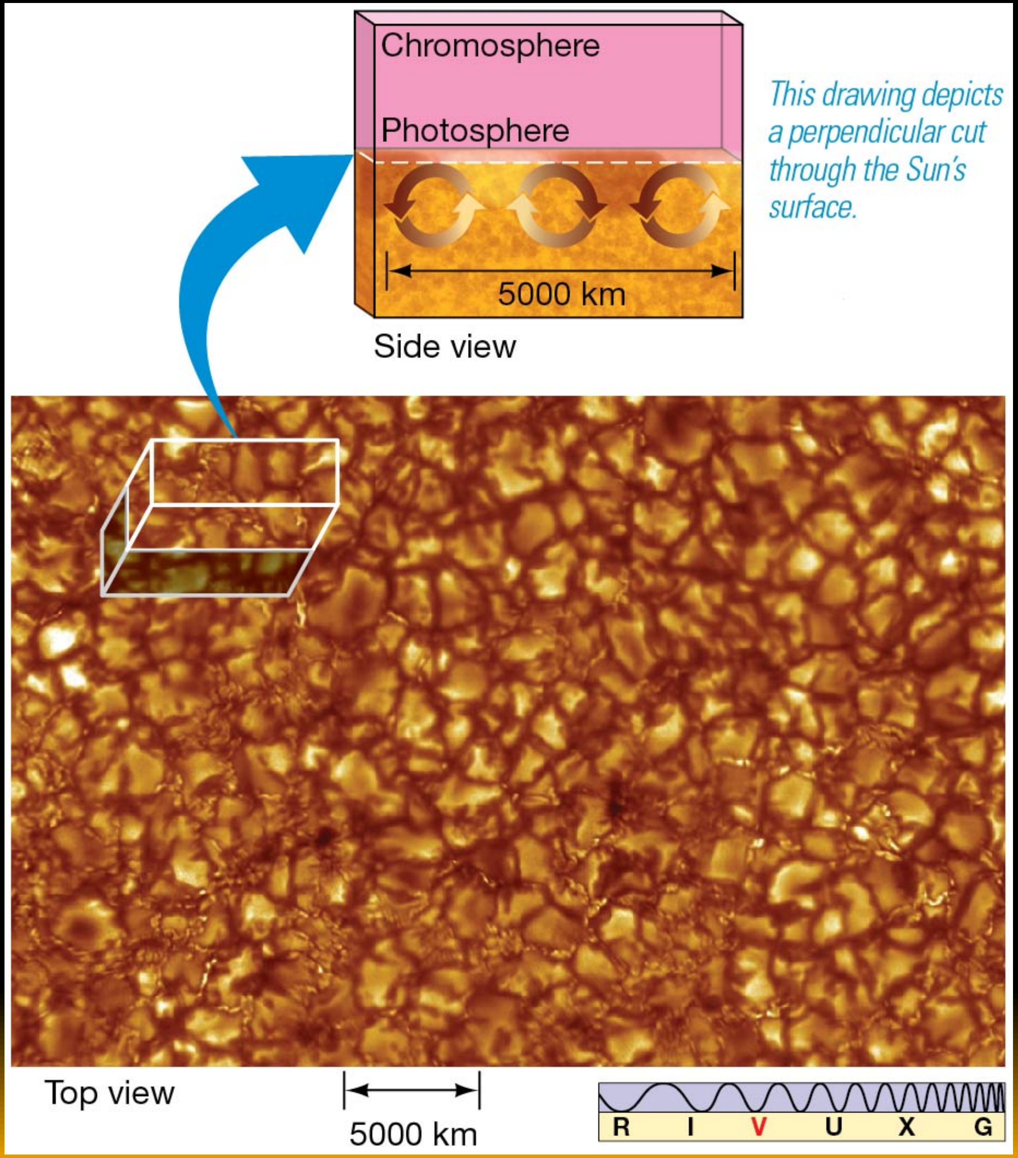
The Photosphere

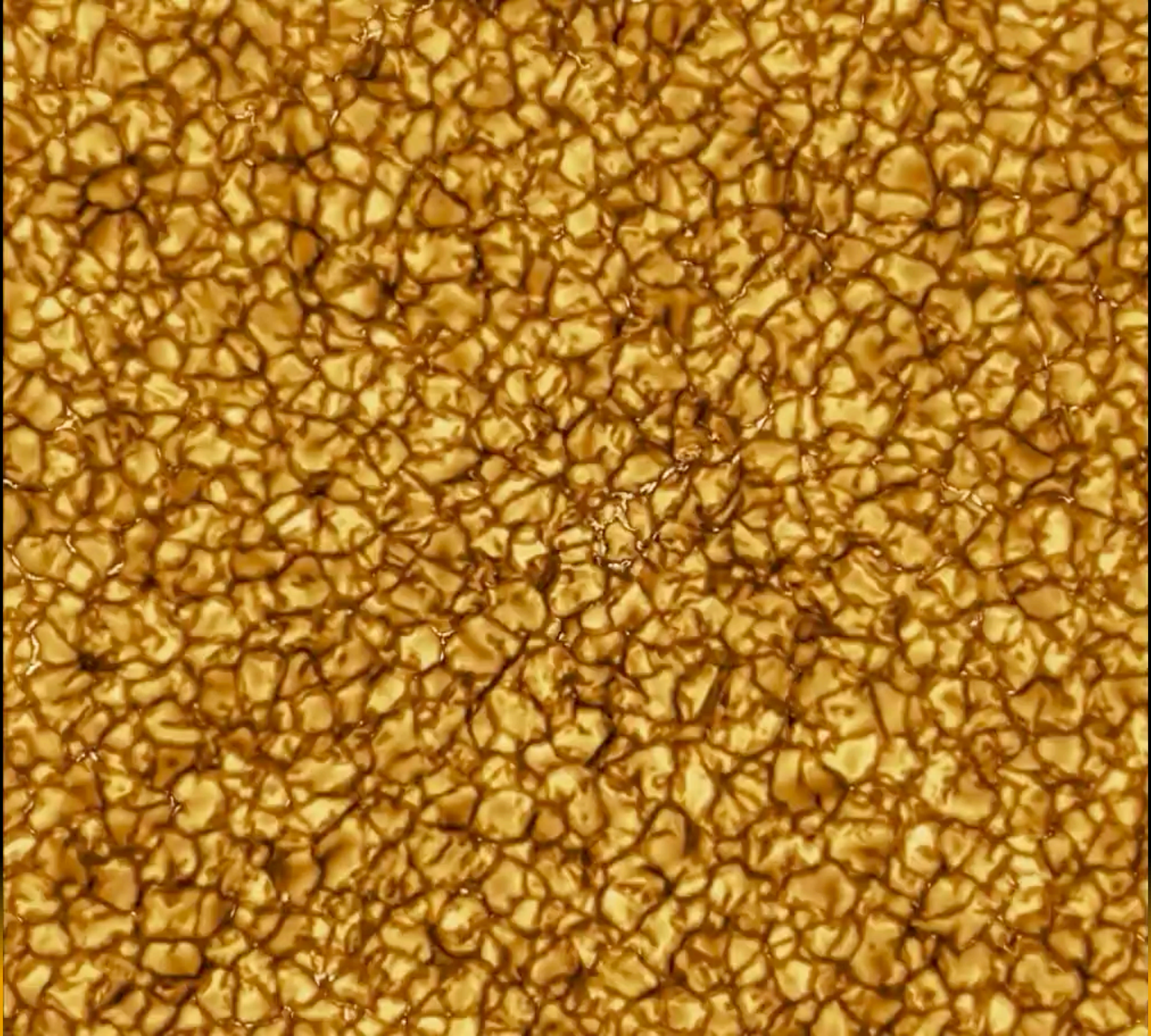
Approaching the surface the solar density falls off rapidly

The gas makes the transition from *completely* opaque to *completely* TRANSPARENT over a very small distance - just a few hundred kilometers!

Radiation (but now from the ionized gas) once again becomes the mechanism of energy transport.

Photons reaching the top of the photosphere escape freely into space.





The Photosphere

The Sun (or shall we say the surface of the Sun) completes one rotation in about a month, but it does not do so as a solid body.

It spins differentially — faster at the equator and slower at the poles, (like Jupiter's and Saturn's spin)

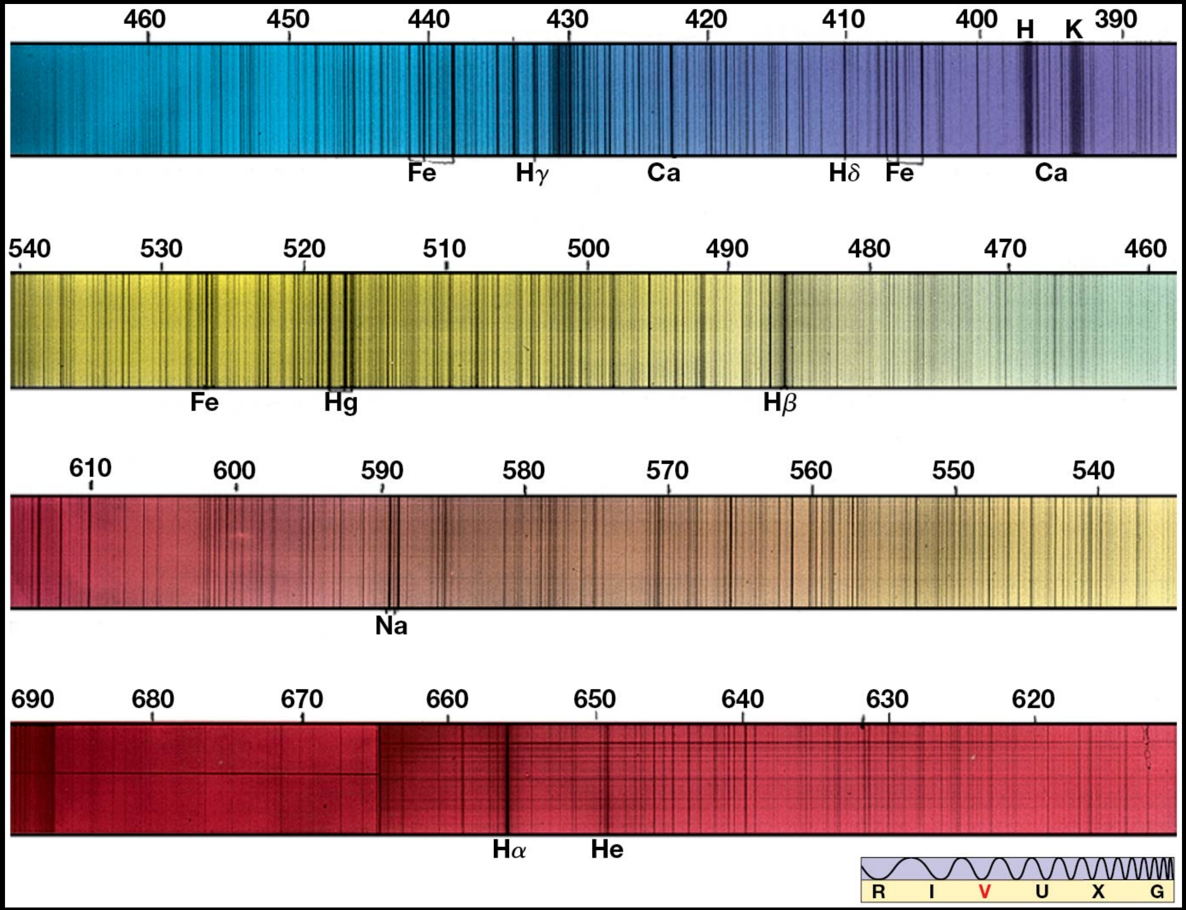
The equatorial rotation period is 25 days. Sunspots are never seen above a 60° latitude (north or south), but there they indicate a 31day period.

TABLE 9.1 Some Solar Properties

Radius	696,000 km
Mass	1.99 × 1030 kg
Average density	1410 kg/m^3
Rotation period	25.1 days (equator)
	30.8 days (60° latitude)
	36 days (poles)
	26.9 days (interior)
Surface temperature	5780 K
Luminosity	3.86×10^{26} W

The Photosphere

A detailed visible spectrum of our Sun shows thousands of dark absorption lines, indicating the presence of 67 different elements in various stages of excitation and ionization in the lower solar atmosphere.



The Photosphere

TABLE 9.2 The Composition of the Sun

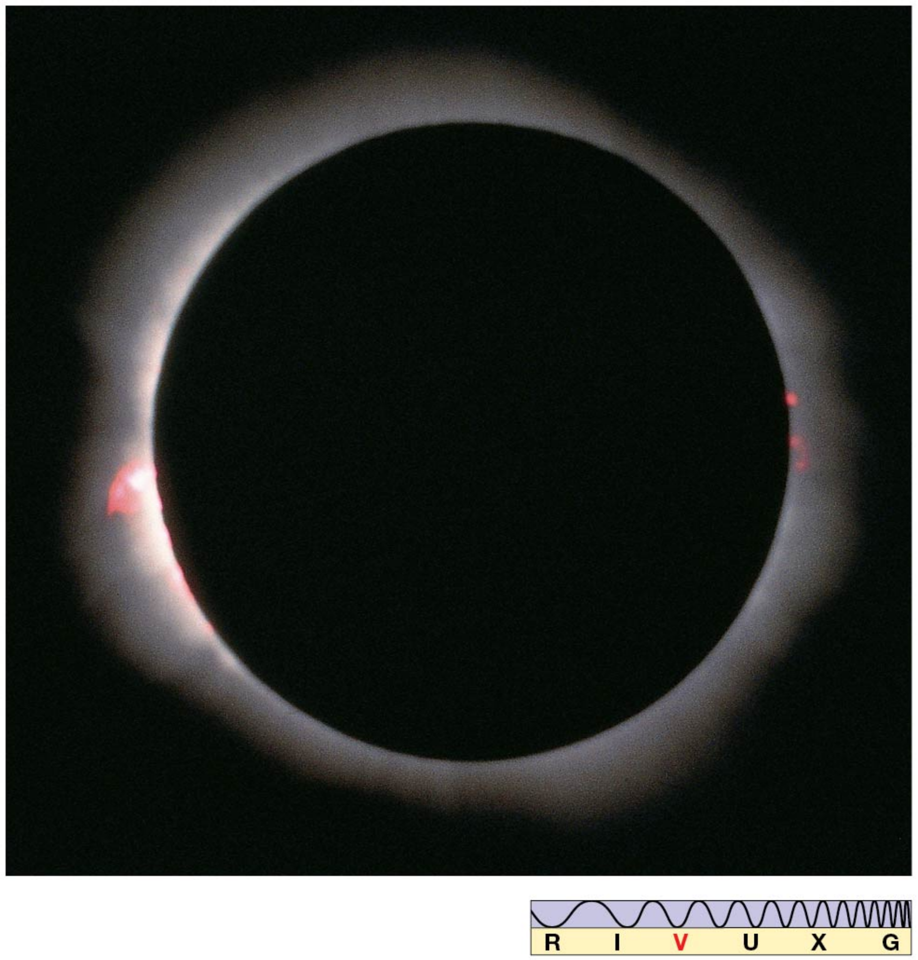
Element	Percentage of Total Number of Atoms	Percentage of Total Mass
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

The Chromosphere

The low density of the chromosphere means that it emits very little light of its own and cannot be observed visually *under normal conditions*.

But during a Solar Eclipse the bright photosphere is obscured by the Moon, but not the *chromosphere*.

The pinkish hue is the result of the red H emission line of hydrogen



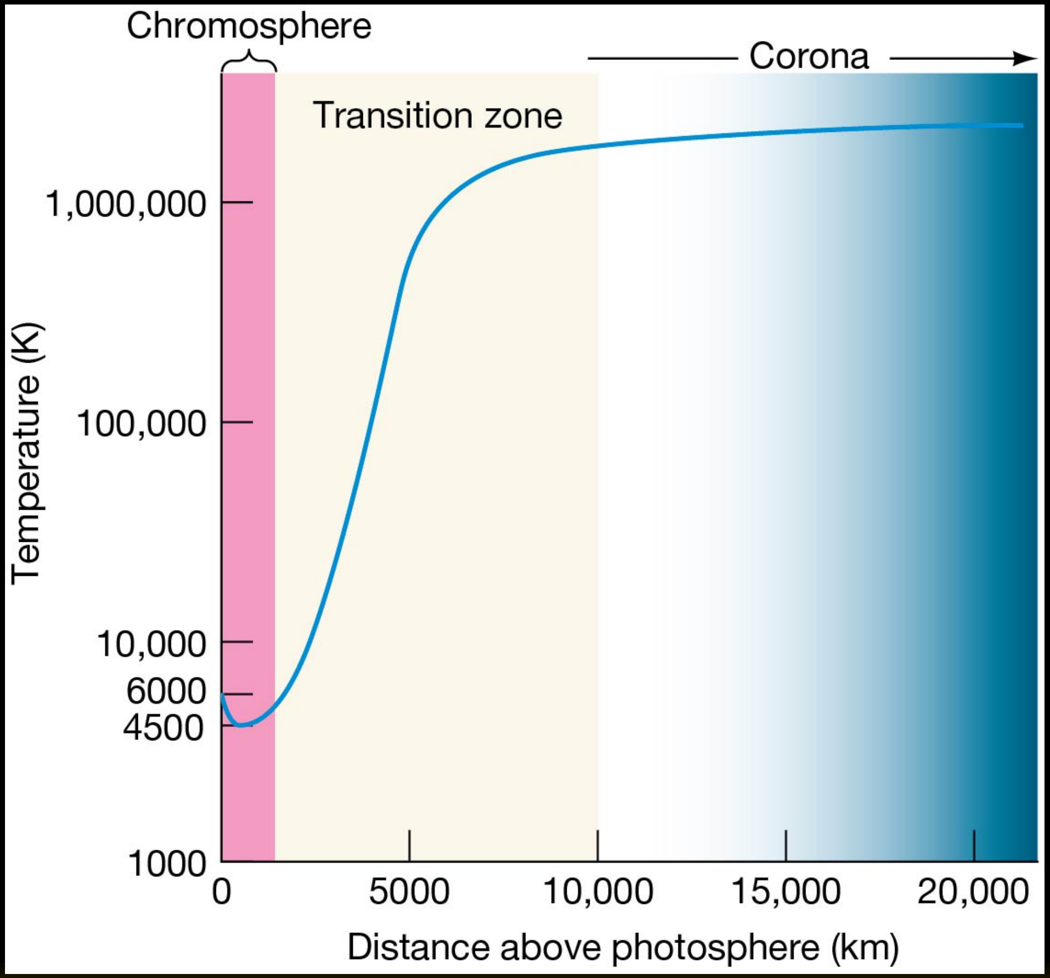
The Transition Zone & Corona

In the transition zone there is a <u>rapid rise in temperature</u> (still not fully understood why)

This temperature profile runs contrary to intuition (<u>moving away</u> from a heat source, we would expect the heat to diminish as the volume increases)

The corona must have another energy source.

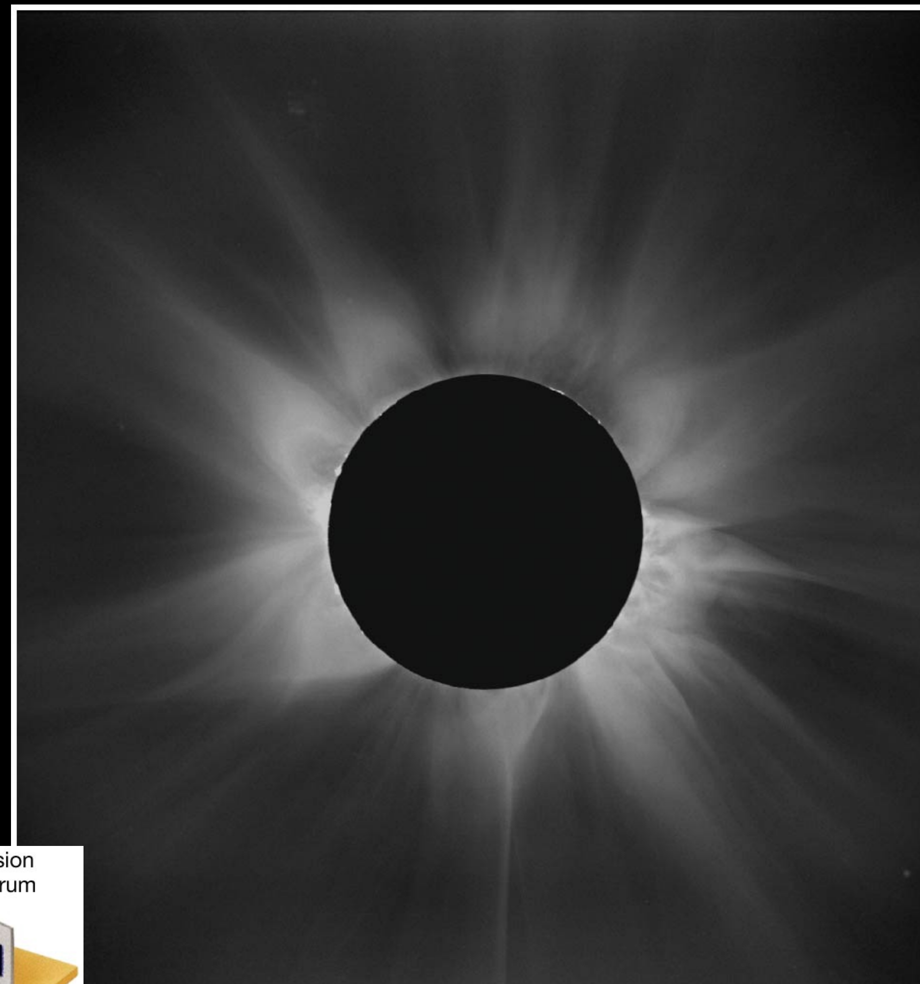
Astronomers think that magnetic disturbances in the photosphere are *responsible* for <u>heating the corona</u>

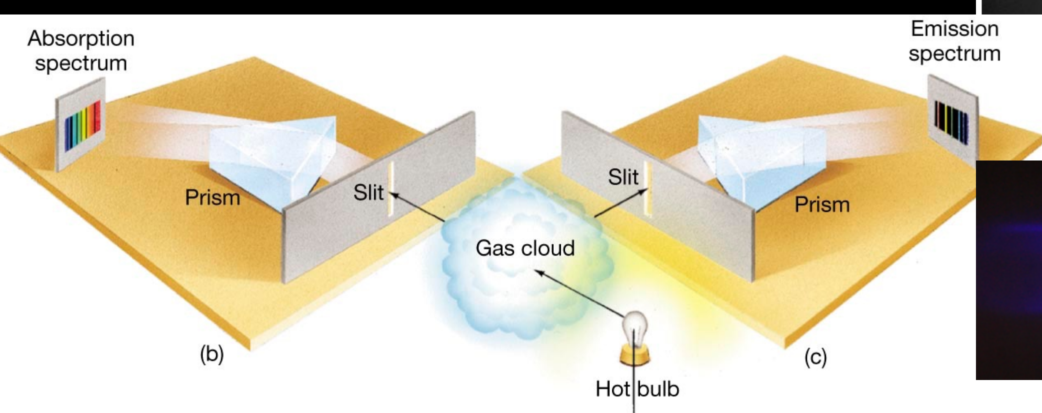


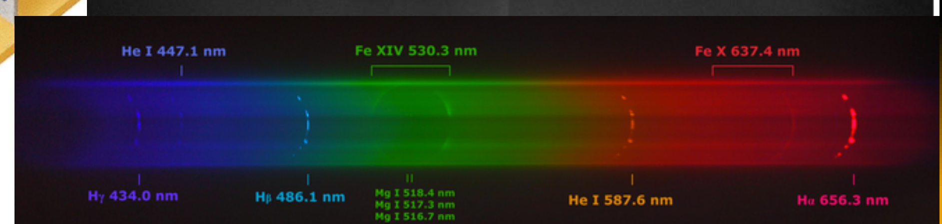
The Corona

Once the solar disk is blocked out the spectrum shifts from absorption to emission, resulting in a <u>new set of spectral lines</u>

These new lines arise because atoms in the corona are *much more* highly ionized compared to atoms in the photosphere or chromosphere.







The Solar Wind

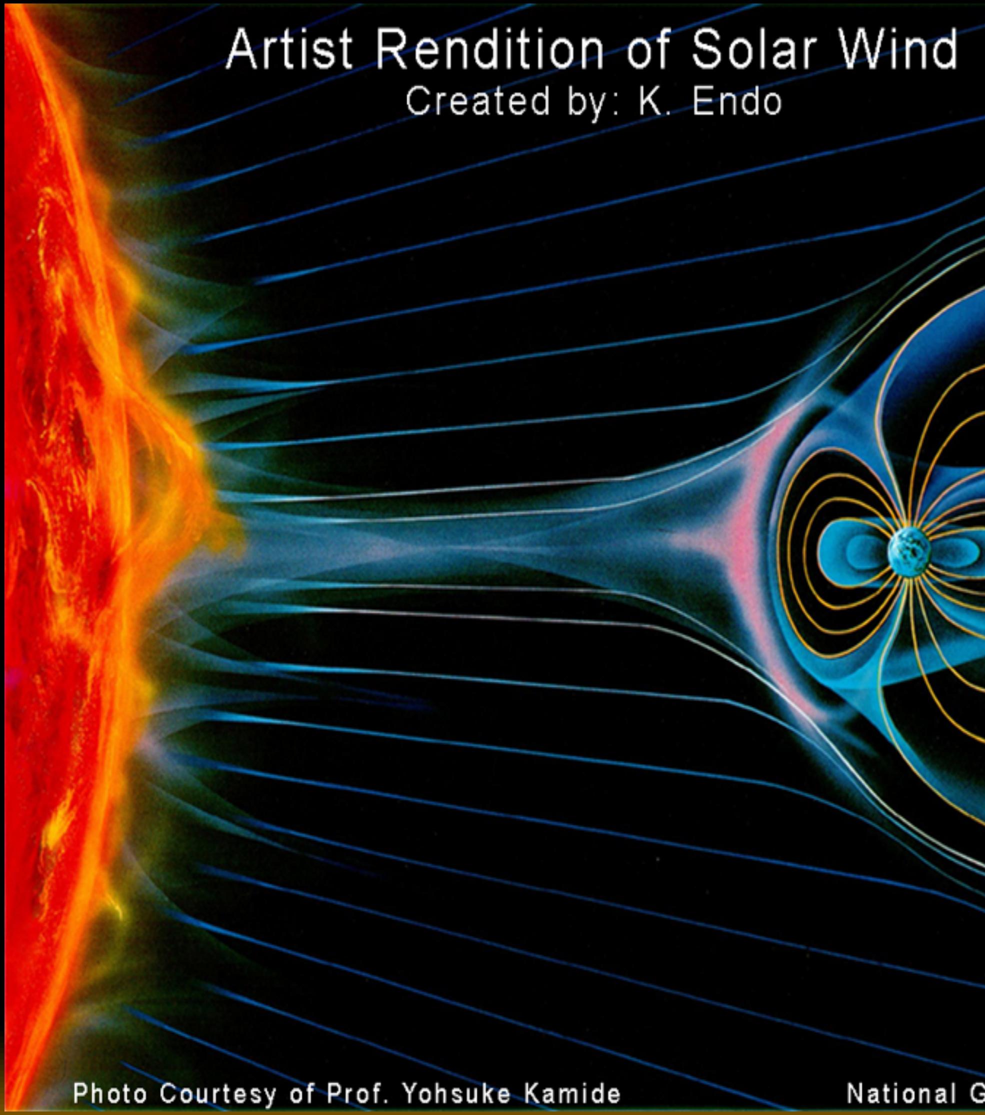
Radiation and fast-moving particles escape from the Sun constantly

The radiation travels at the *speed of light*, taking 8 minutes to reach Earth.

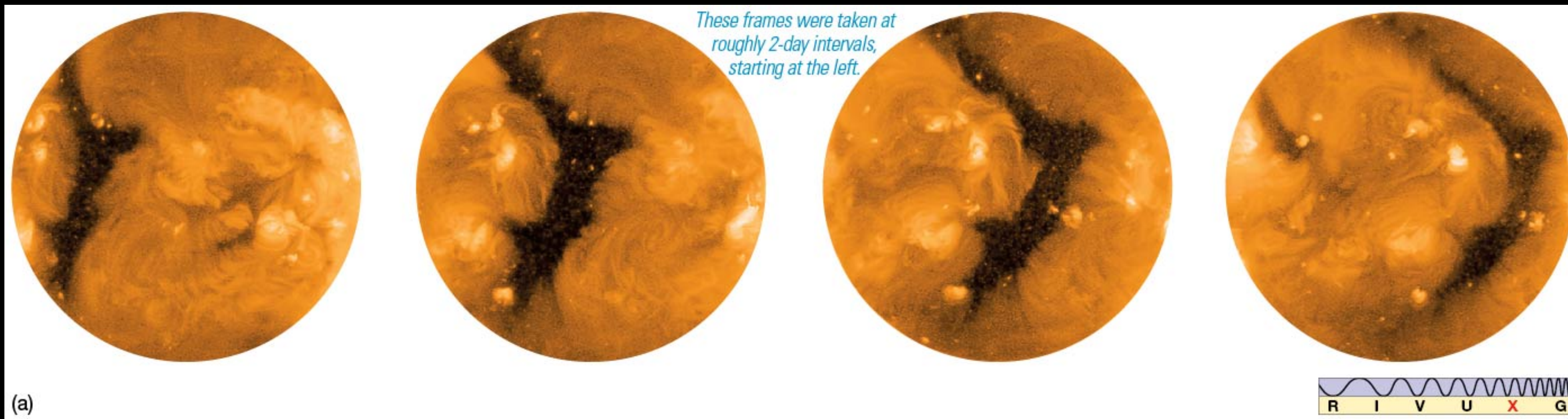
But particles - mostly protons and electrons - move at *500 km/s* and reach the Earth in a few days

The Solar wind is extremely thin but still it carries away million tons (2 billion pounds) of solar matter *every second!*

The Sun has lost only 0.1 percent of it's mass in it's 4.6 billion years life due to this *"evaporation"*



The Solar Wind

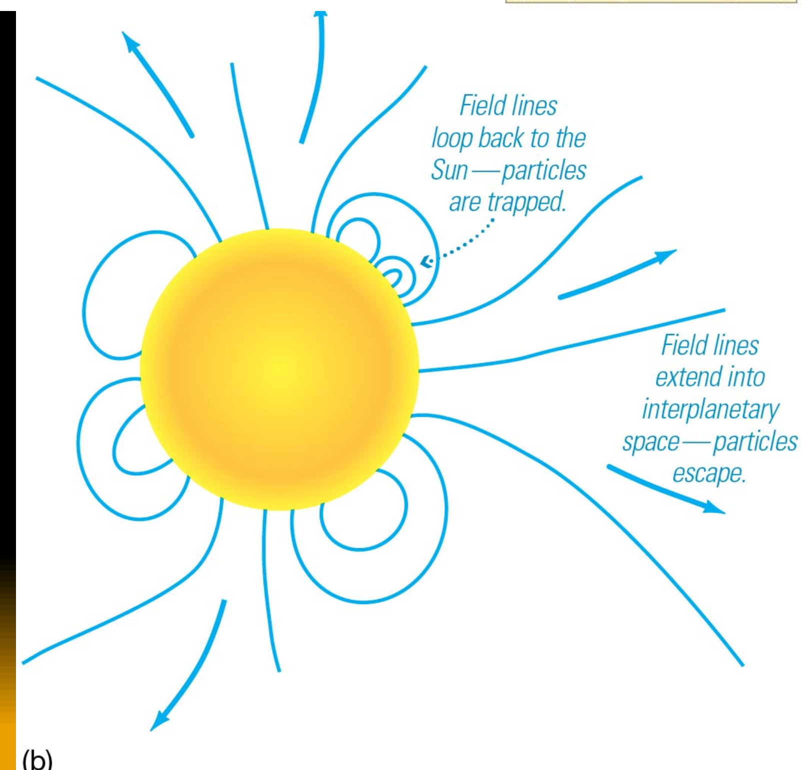


(a)

In a Coronal Hole <u>charged particles</u> follow magnetic field lines and compete with the Sun's *gravity*

A trapped field line *loops back* toward the photosphere and the particles follow and are <u>also trapped</u>

Otherwise particles <u>escape</u> as part of the solar wind



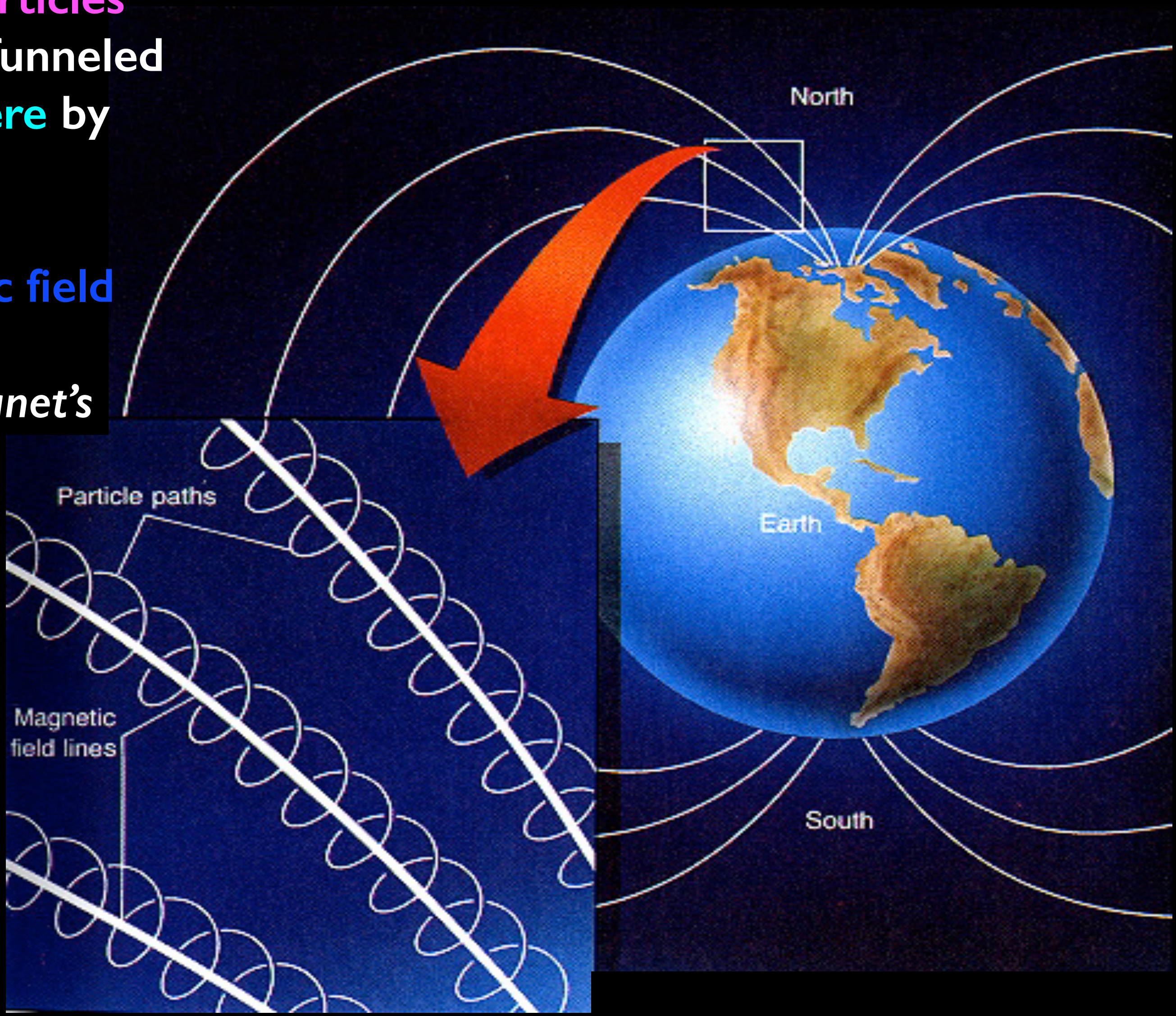
(b)

The Solar Wind

When the charged particles reach Earth they are funneled down to the ionosphere by our magnetic field

Without our magnetic field the Solar Wind would <u>bombard</u> all of the *planet's surfaces*

Auroras



The Solar Wind

The result: The Aurora Borealis

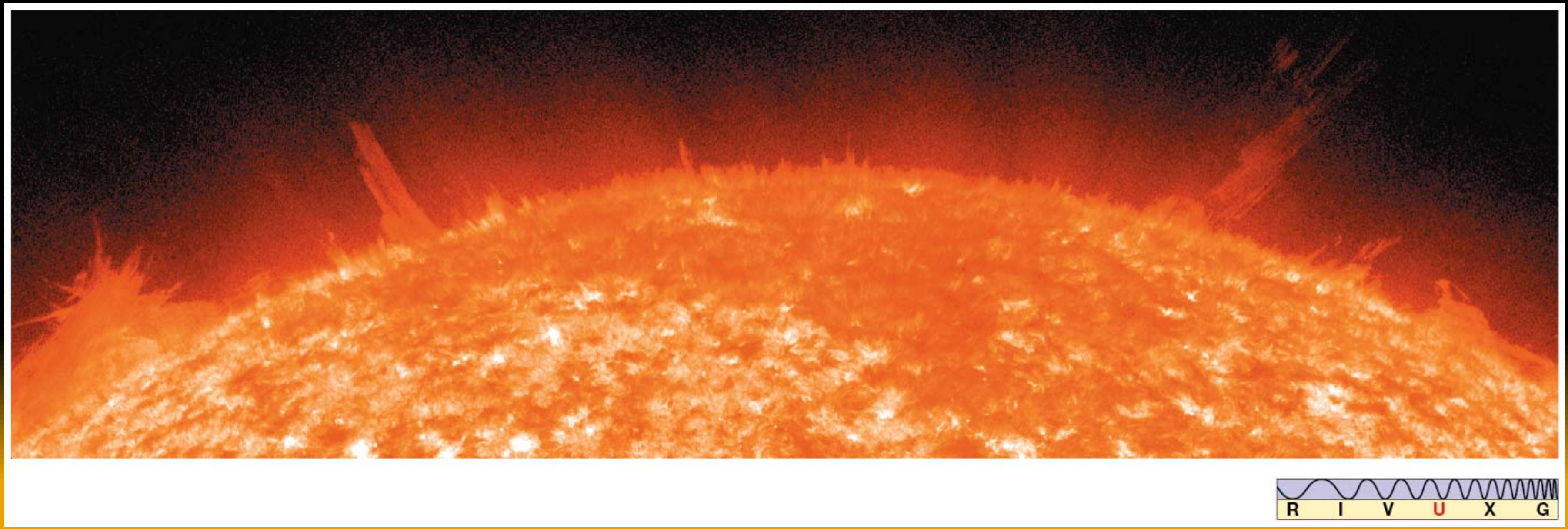
Solar Weather

https://youtu.be/l3QQQu7QLoM

Solar Weather

It has been shown that the strength of the solar wind is *strongly influenced* by the level of solar activity (weather), and this, in turn, directly affects Earth's magnetosphere and possibly, through the myriad of electrical devices we have today, the affairs of Humankind.

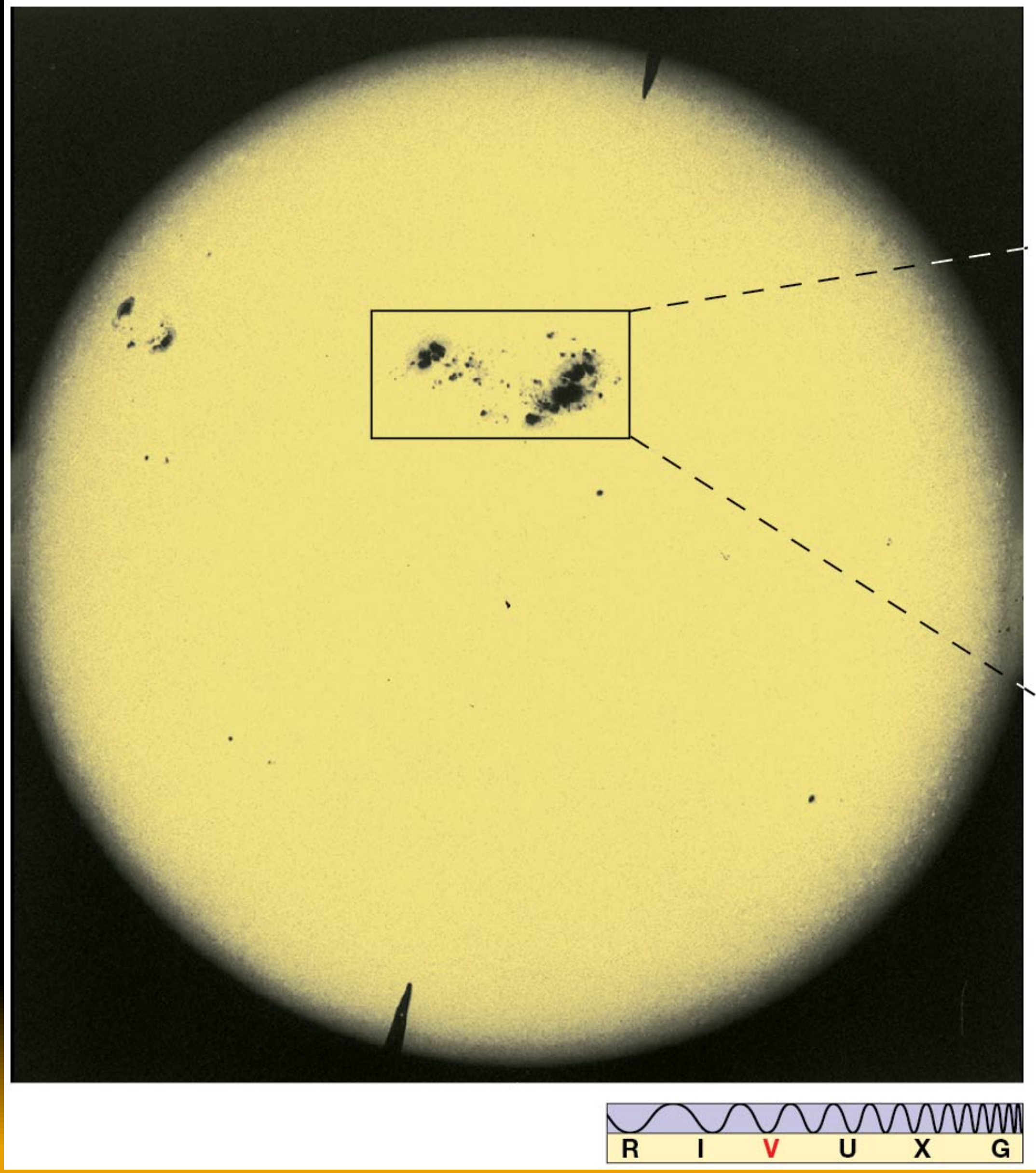
We turn our attention now to the activity on the surface of the Sun.



I. Sun Spots

Sun spots typically measure about 10,000 km across - about the size of Earth.

At any given instant, the Sun may have hundreds of sunspots, <u>or</u> it may have none at all.

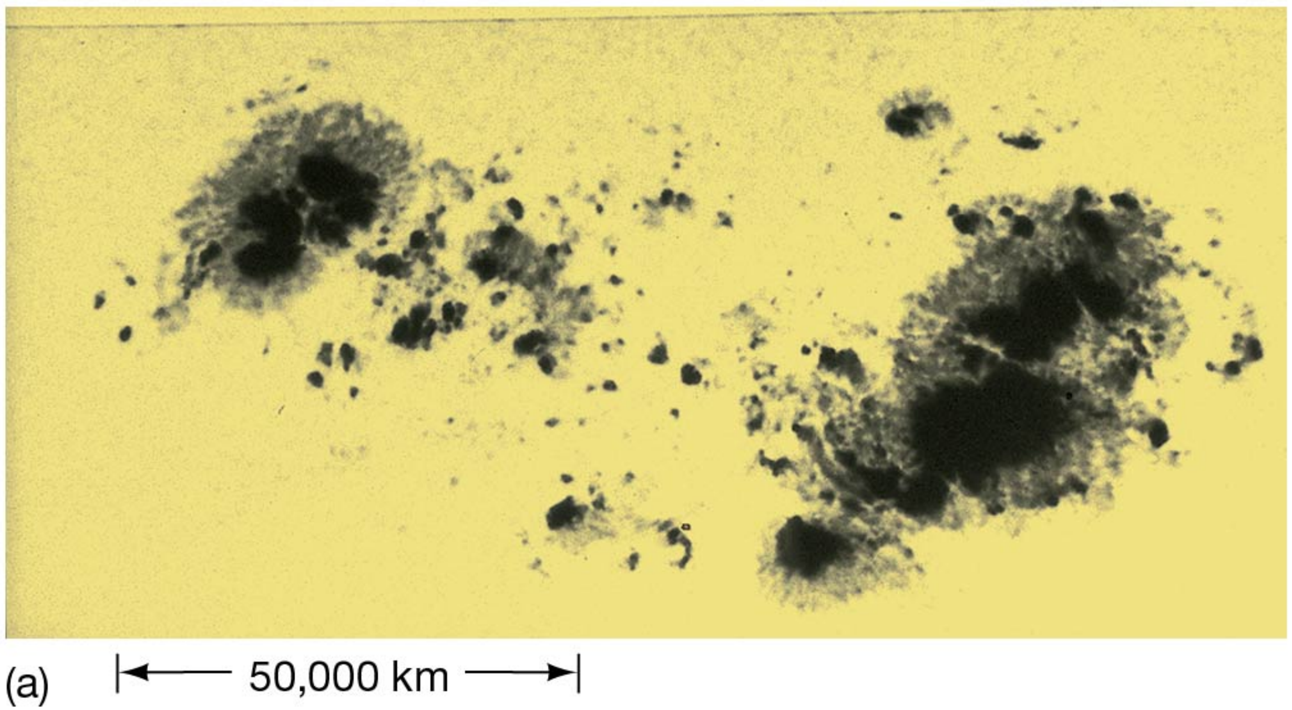


I. Sun Spots

Sunspots are simply cooler regions of the photospheric gas.

The magnetic field in a typical sunspot is about <u>1000 times greater</u> than it’s surrounding

This surrounding field is itself *several times stronger* than Earth’s magnetic field.

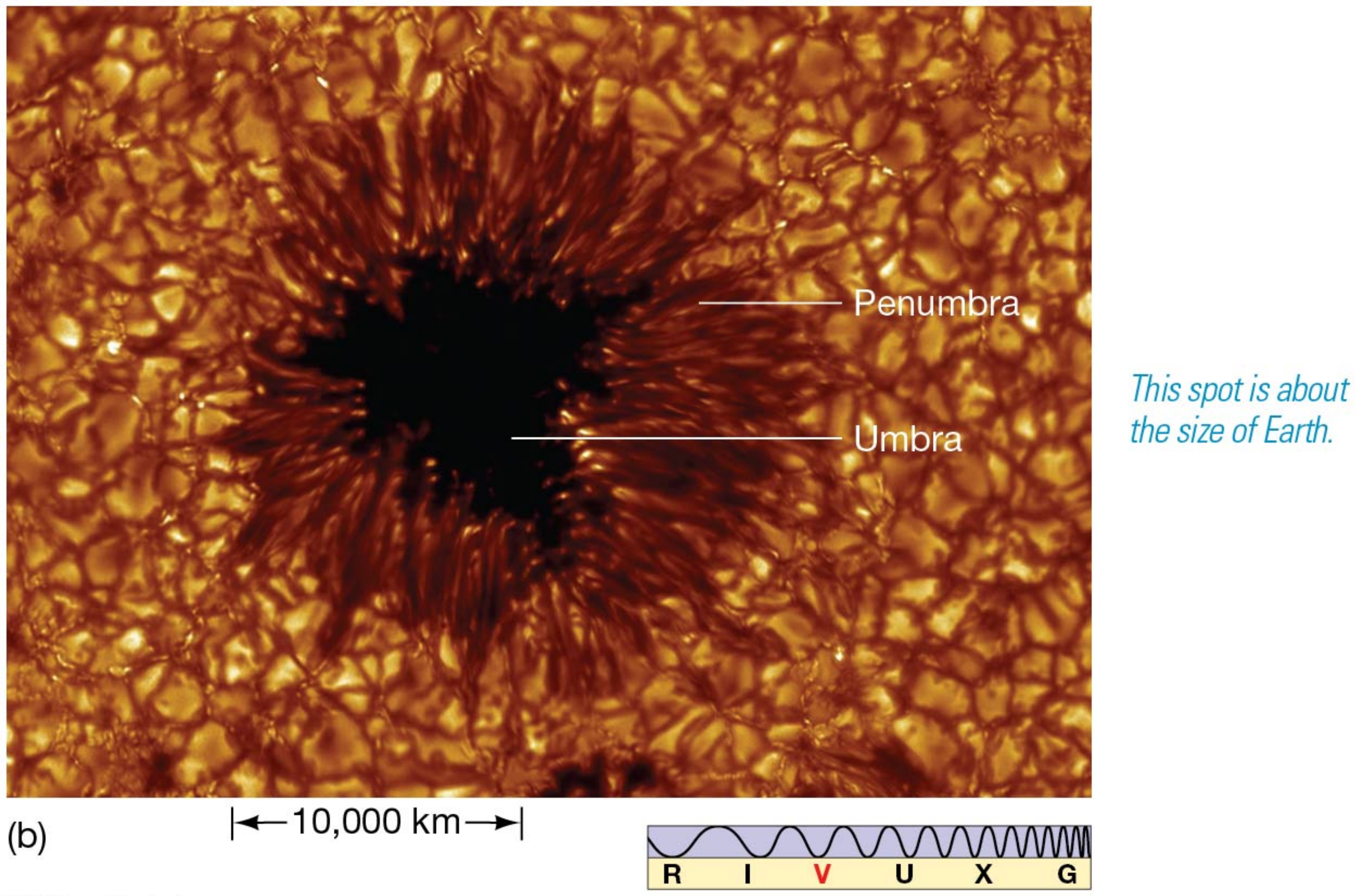


Sunspots appear dark because they are slightly cooler than the surrounding gas.

I. Sun Spots

The umbra (4500K) is surrounded by a grayish penumbra (5500K) which is surrounded by undisturbed photosphere (5800K).

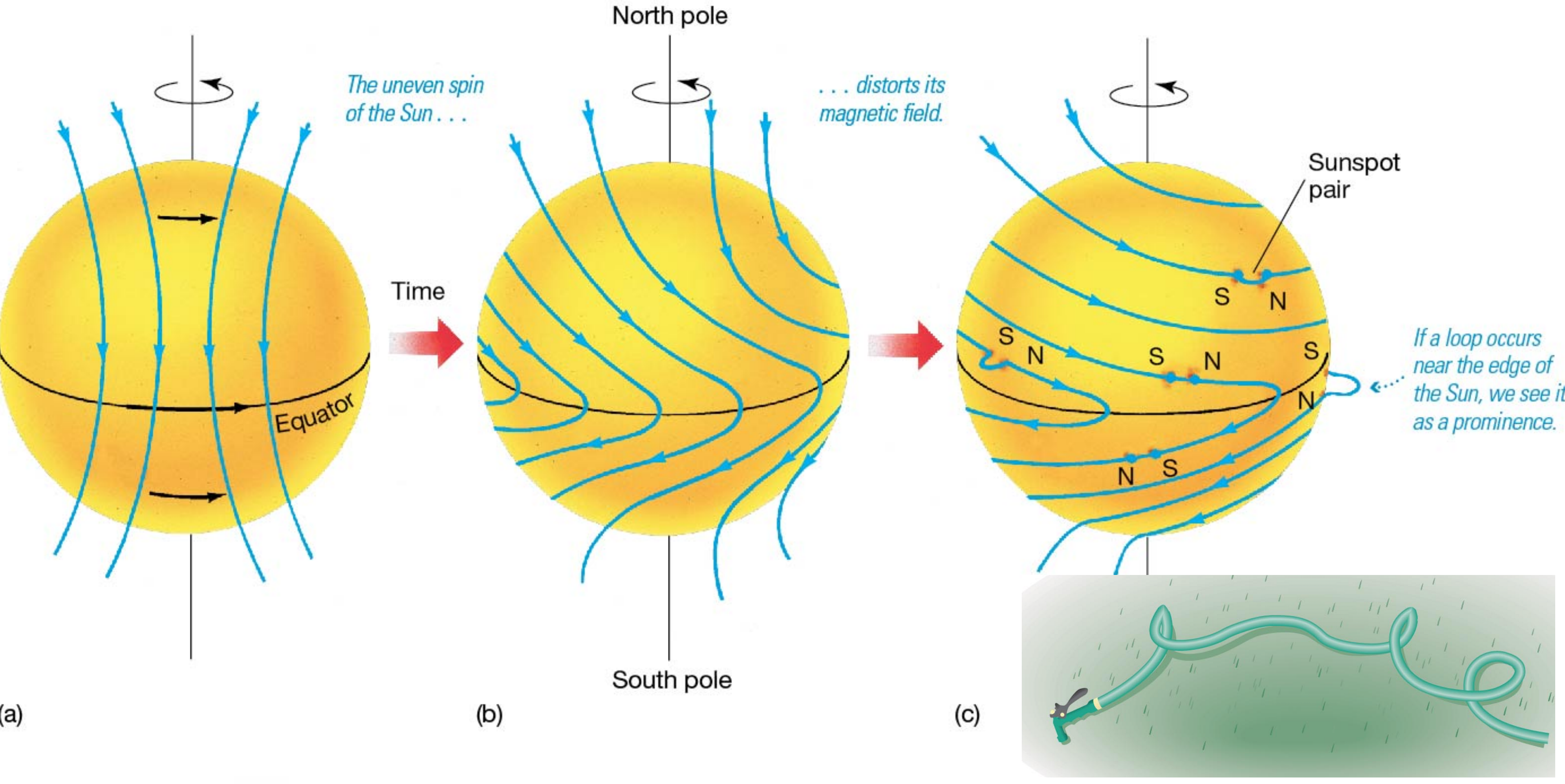
They seem dark *only* because they appear against an even brighter background



I. Sun Spots

The <u>interaction</u> between the Sun's differential rotation and convection *radically effects* the character of the magnetic field

This causes a contortion of the field lines resulting in a <u>protrusion</u> of some



I. Sun Spots

Magnetic Properties

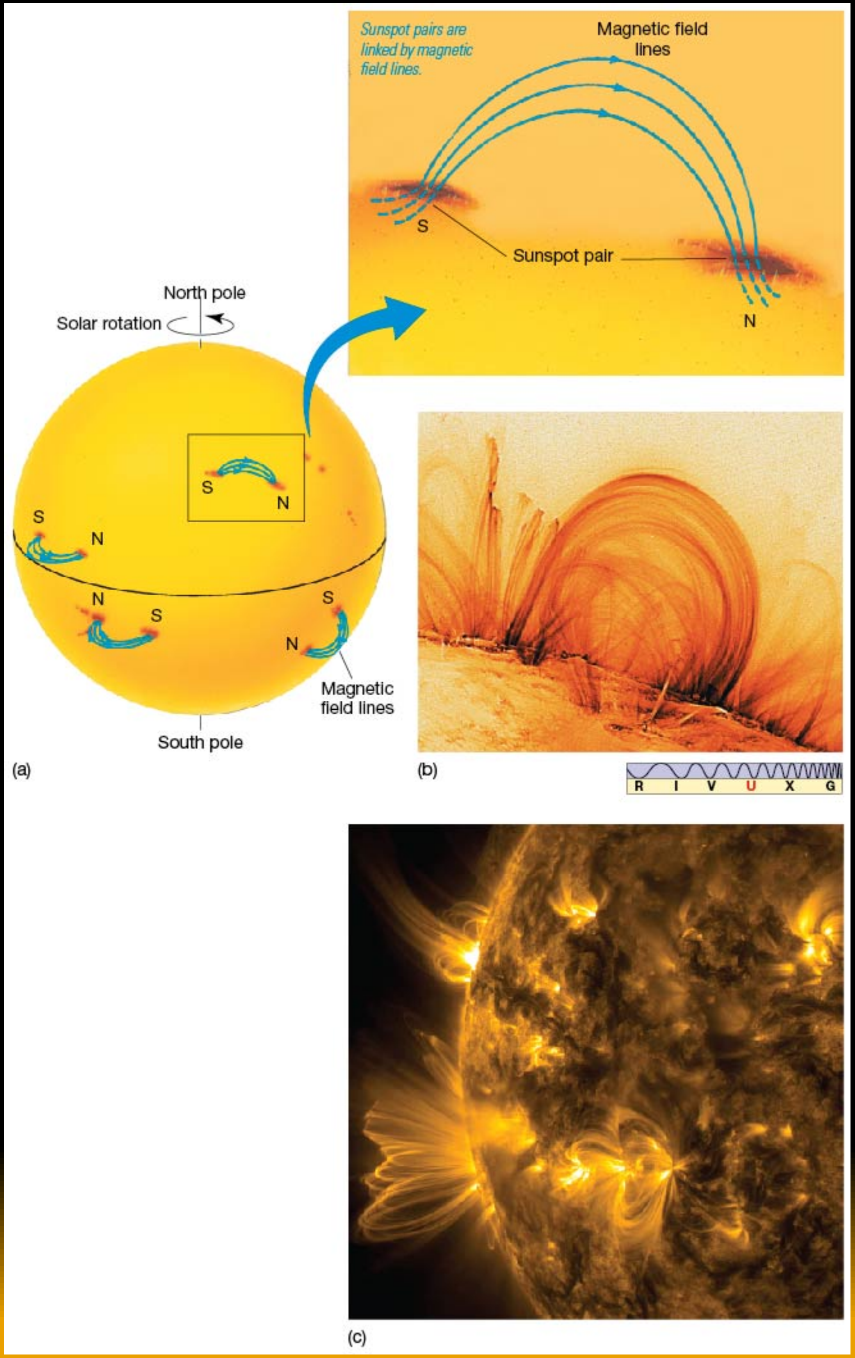
Sunspots almost always come in pairs which lie at roughly the same latitude.

All the sunspot pairs in the same solar hemisphere at any instant have the same magnetic configuration.

- All leading spots in a given hemisphere have the same polarity, either North or South.

- All leading spots in the opposite hemisphere have the opposite polarity.

We call the material torn away from the surface Solar Prominences (discussed later)



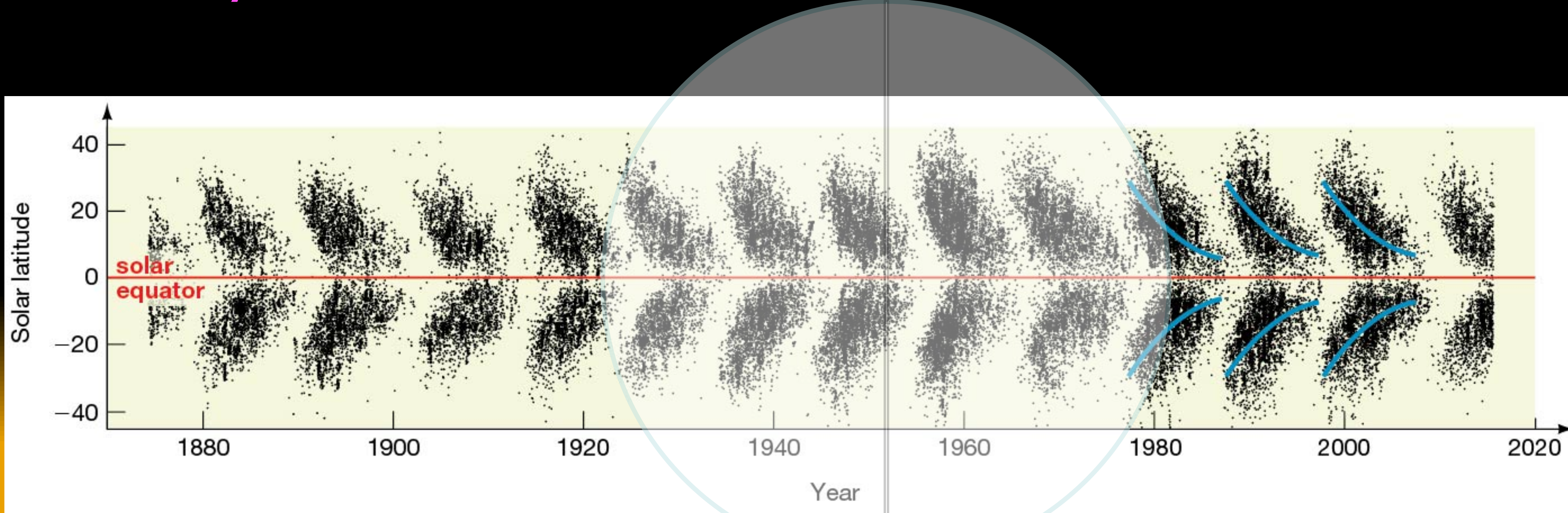
I. Sun Spots

Observations have established a clear sun spot cycle.

The average number of spots reaches a maximum every 11 years, then falls off almost to zero before the cycle begins afresh.

As older spots at higher latitudes *fade* new spots appear closer to the equator (individual sunspots do not move once formed)

In fact, the 11-year cycle is only half of a 22-year solar cycle: the polarities of the leading spots on a *given hemisphere* reverse for the next 11 years.

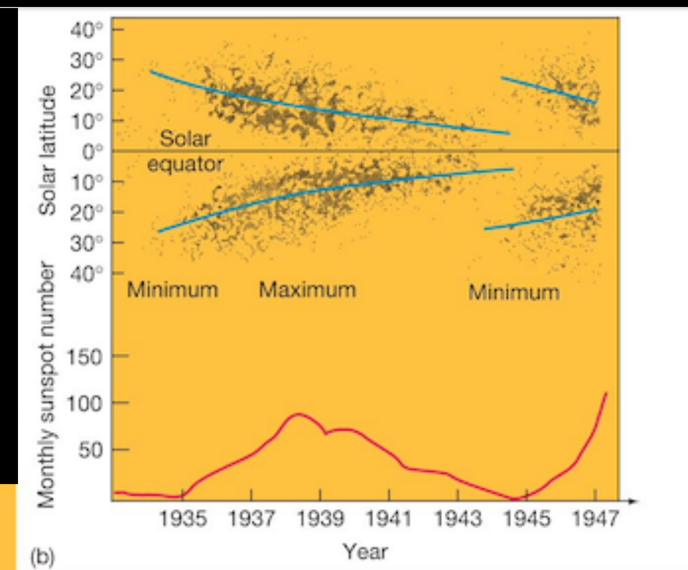


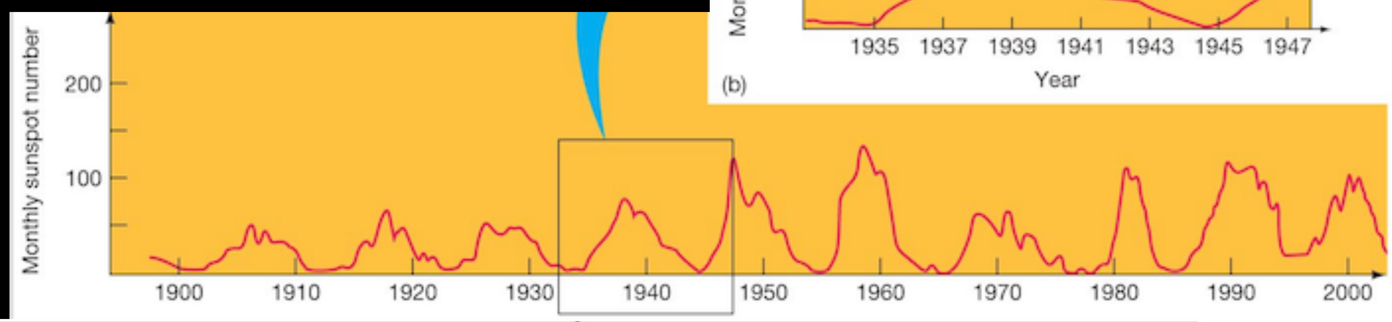
I. Sun Spots

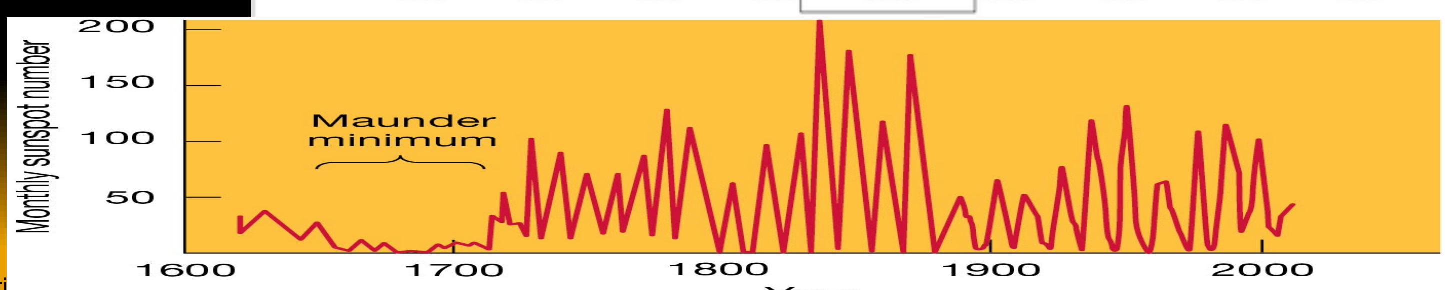
But <u>not all</u> is so simple: there are *cycles* to the *cycles*

A lengthy period of <u>solar inactivity</u> occurred from 1645 to 1715, called the Maunder minimum: it <u>corresponded</u> to the Little Ice Age that *chilled* northern Europe during the late 17th century

More recently is the sunspot *minimum* in 2008/9: it has resulted in the <u>least active</u> Sun in almost a century







II. Solar Prominences

Solar prominences (also referred to as filaments) - are loops or sheets of glowing gas ejected from an active region on the solar surface.

Prominences move through the inner parts of the corona under the influence of the Sun's magnetic field.

Magnetic *instabilities* in the strong fields found in and near sunspot groups may cause the prominences, although the details are still not completely understood.

A typical solar prominence measures some 100,000 km in extent, nearly 10 X Earth. Some may persist for days or even weeks.

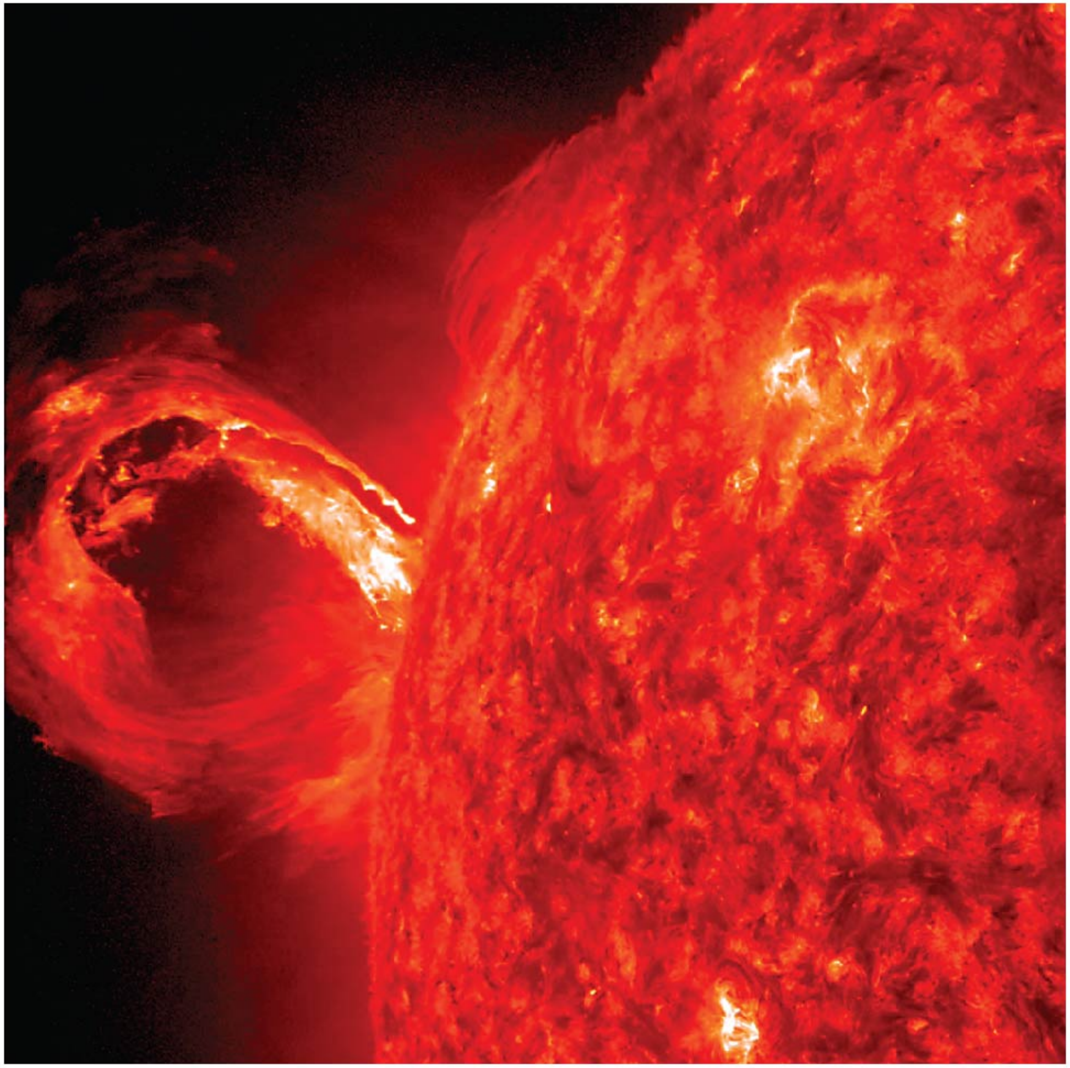
III. Solar Flares

Flares are another type of solar activity observed near active regions

Flares are <u>much more violent</u> than prominences and are the *result* of magnetic instabilities

Flares flash *across a region* of the Sun in minutes, <u>releasing</u> enormous amounts of energy

Temperatures in the <u>extremely compact hearts</u> of flares can reach 100 million K (six times hotter than the solar core).



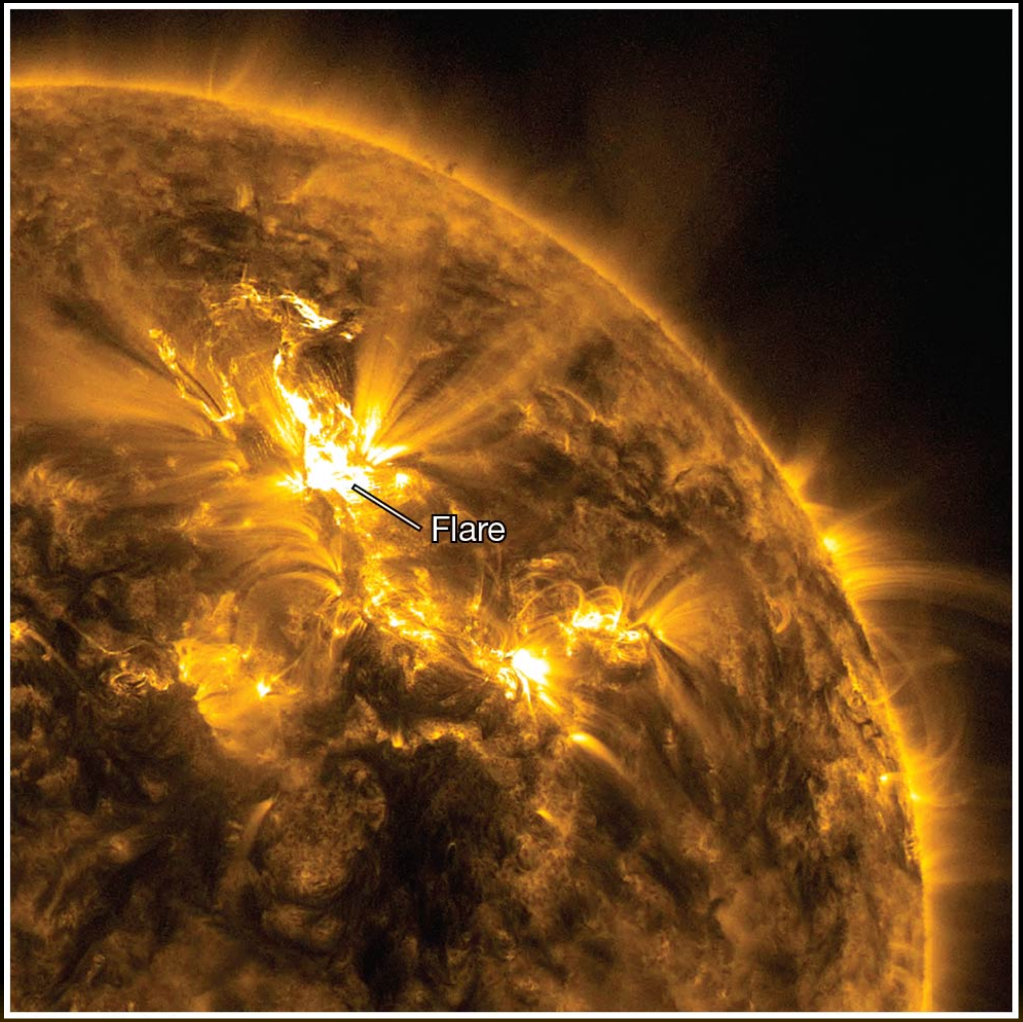
(a)

III. Solar Flares

The flares are so energetic that the Sun's magnetic field is *unable to hold them*

Instead, the particles are simply blasted into space by the violence of the explosion.

Flares are thought to be responsible for the internal pressure waves that *generate* the surface oscillations.



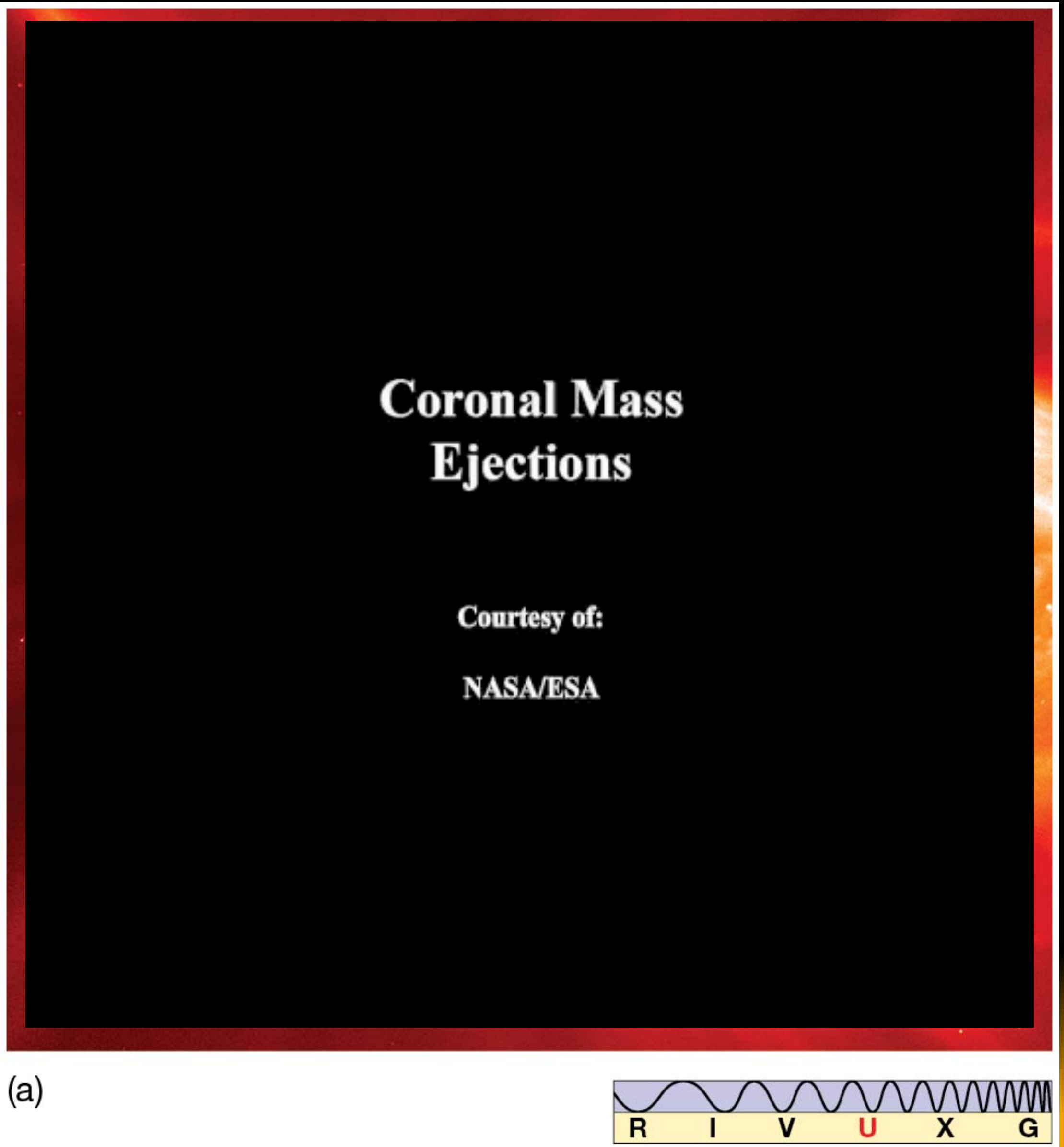
IV. Coronal Mass Ejections

A coronal mass ejection is a giant magnetic "bubble" of ionized gas separating from the solar atmosphere and *escaping* into interplanetary space.

At the solar minimum CMEs occur about once per week

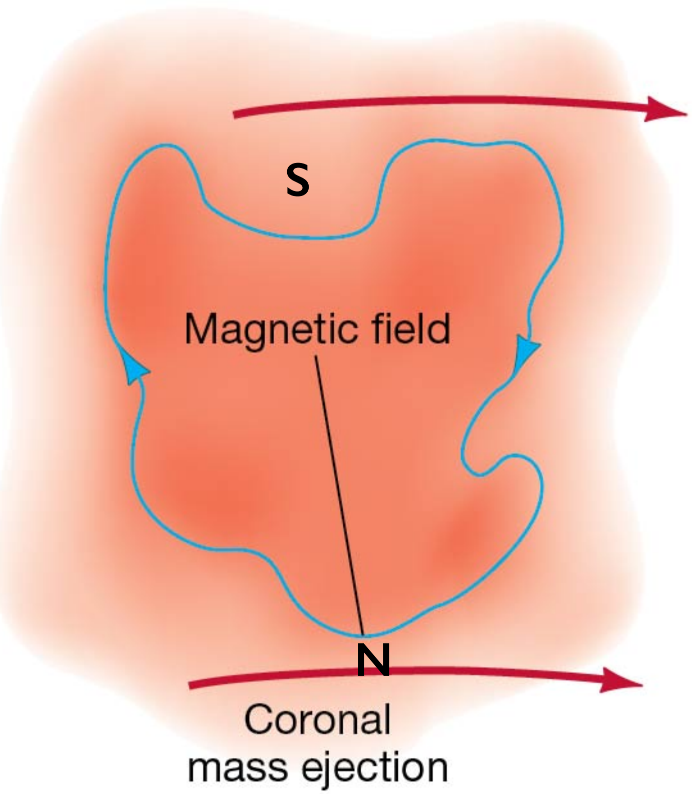
CMEs occur two or three times per day at solar maximum

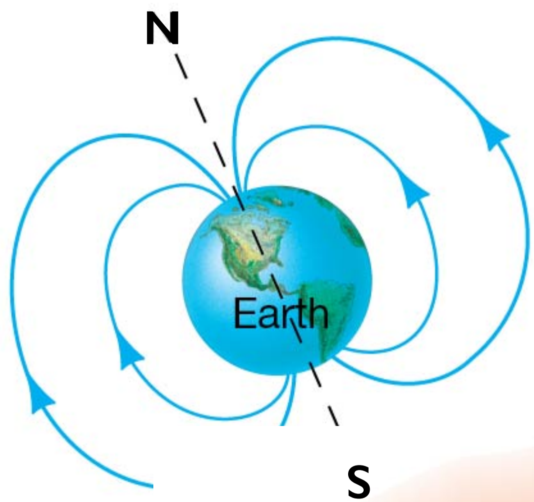
Carrying an enormous amount of energy they cause power disruptions on our planet

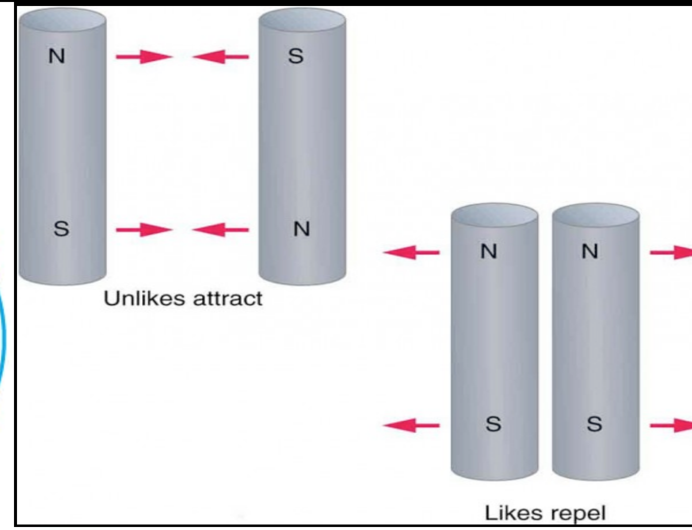


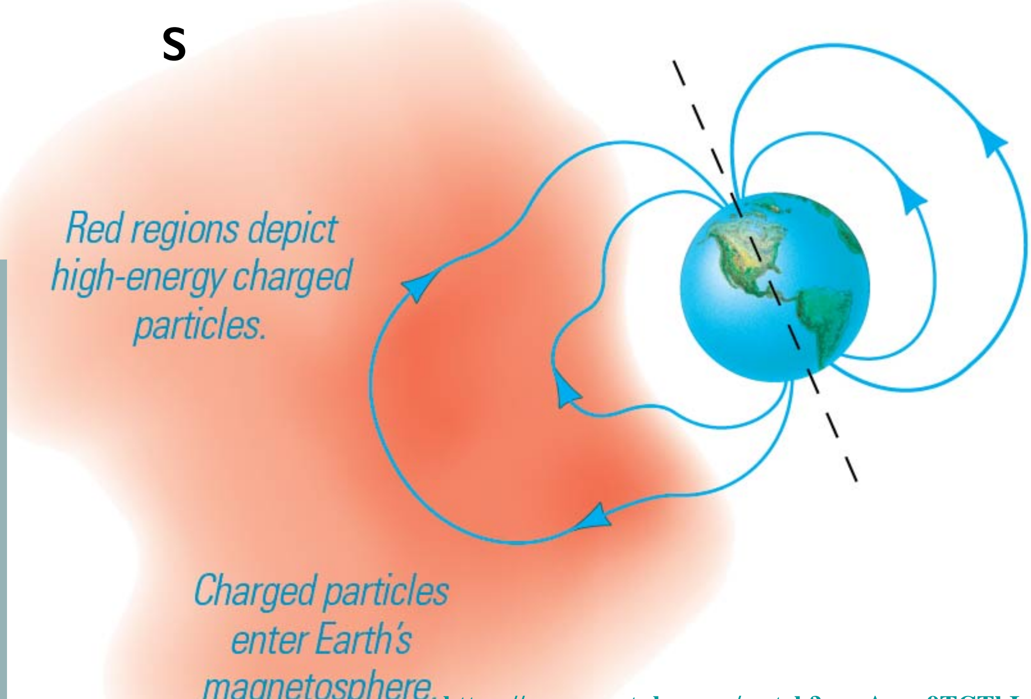
(a)

IV. Coronal Mass Ejections









If CME fields are <u>properly oriented</u> with Earth's field then 'reconnection' occurs

This <u>dumps energy</u> into the Earth's magnetosphere and can potentially *cause widespread* grid disruptions

https://en.wikipedia.org/wiki/Solar_storm_of_1859
https://www.history.com/news/a-perfect-solar-superstorm-the-1859-carrington-event
https://www.youtube.com/watch?v=uAuyv9TCThI
https://www.youtube.com/watch?v=JncTCE2NWgc

The Solar Core

The Solar Core

We now conclude our Solar Tour in the Core

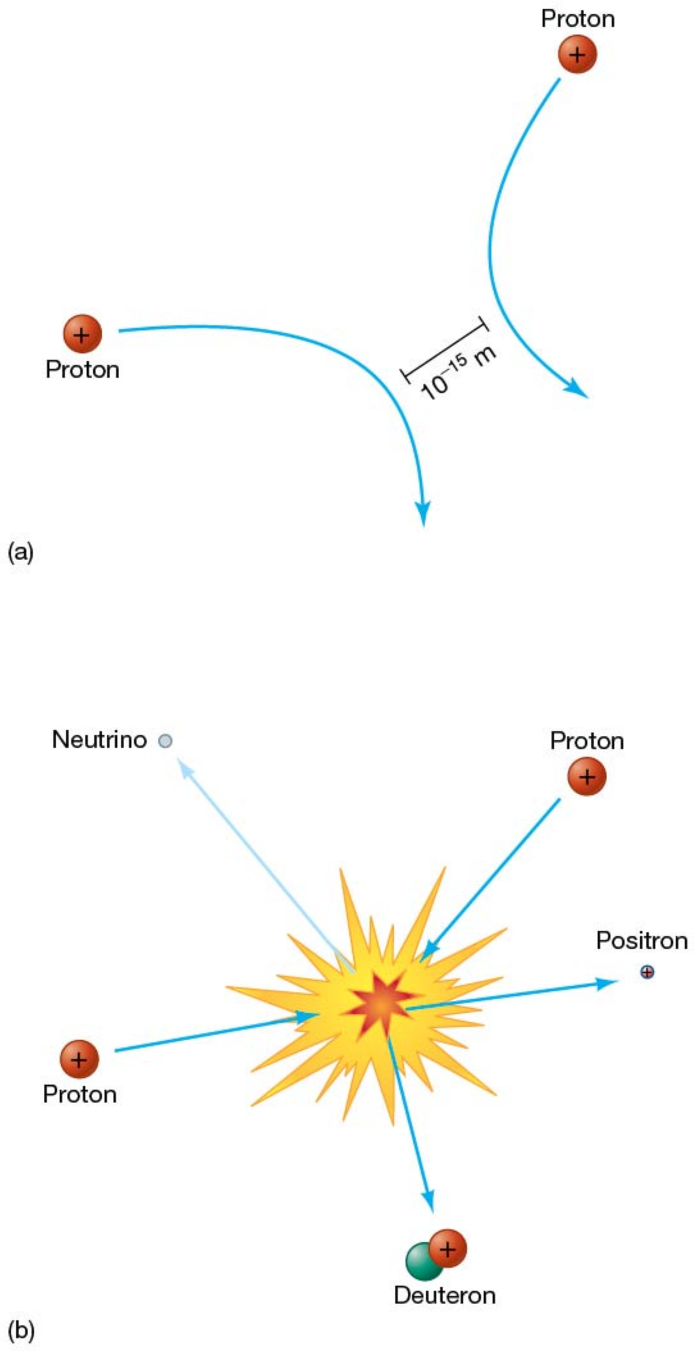
The temperature (a term for particle velocity) is so high that when protons collide they *overcome* their Coulomb repulsion and allow the nuclear Strong Force to act

This Strong Force, one of the four forces of nature, pulls the protons together

This violent collision triggers nuclear fusion releasing the energy that powers the Sun

Speeds of a few hundred kilometers per second are *needed* to slam protons together fast enough to initiate fusion

These high speeds are associated with extremely high temperatures - 10 million K !



The Solar Core

During a fusion reaction the mass of the resultant nucleus is less than the combined masses of colliding nuclei

Q: Where does that mass go?

A: It is converted to energy according to Einstein's equation: $E = Mc^2$

The speed of light is so large that even a small amount of mass *translates* into an enormous amount of energy

The process is an example of the law of conservation of mass and energy

This states that the sum of mass and energy (properly converted using Einstein's equation) must always remain constant in any physical process.

There are no known exceptions.

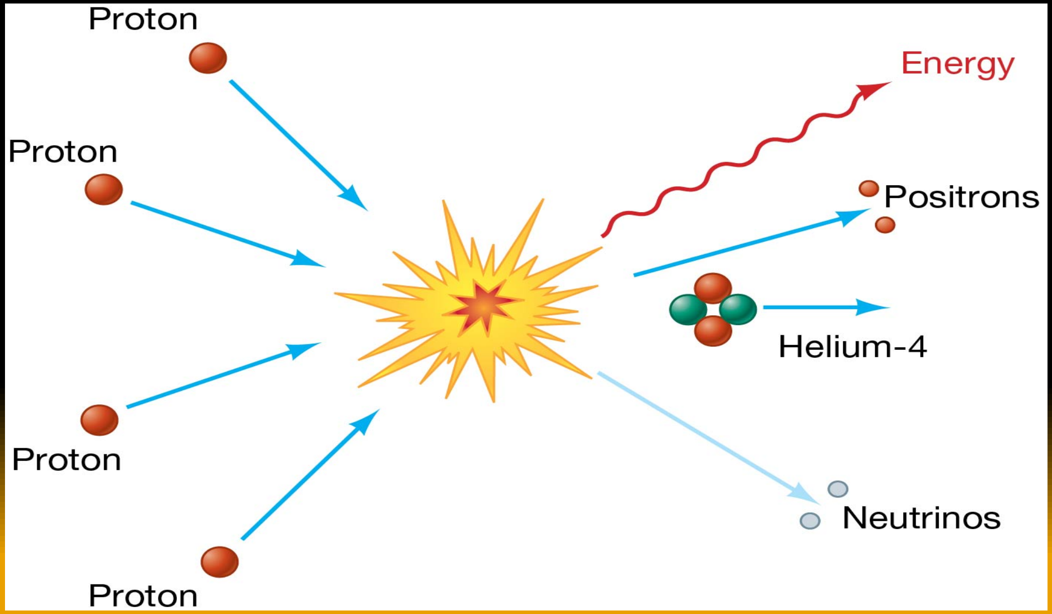
The fact that energy emanates from the Sun means it's *mass must be decreasing* with time.

The Proton–Proton Chain Simplified

Input: Six protons
Output: Helium-4 nucleus, photons and two new particles, a positron and a neutrino.

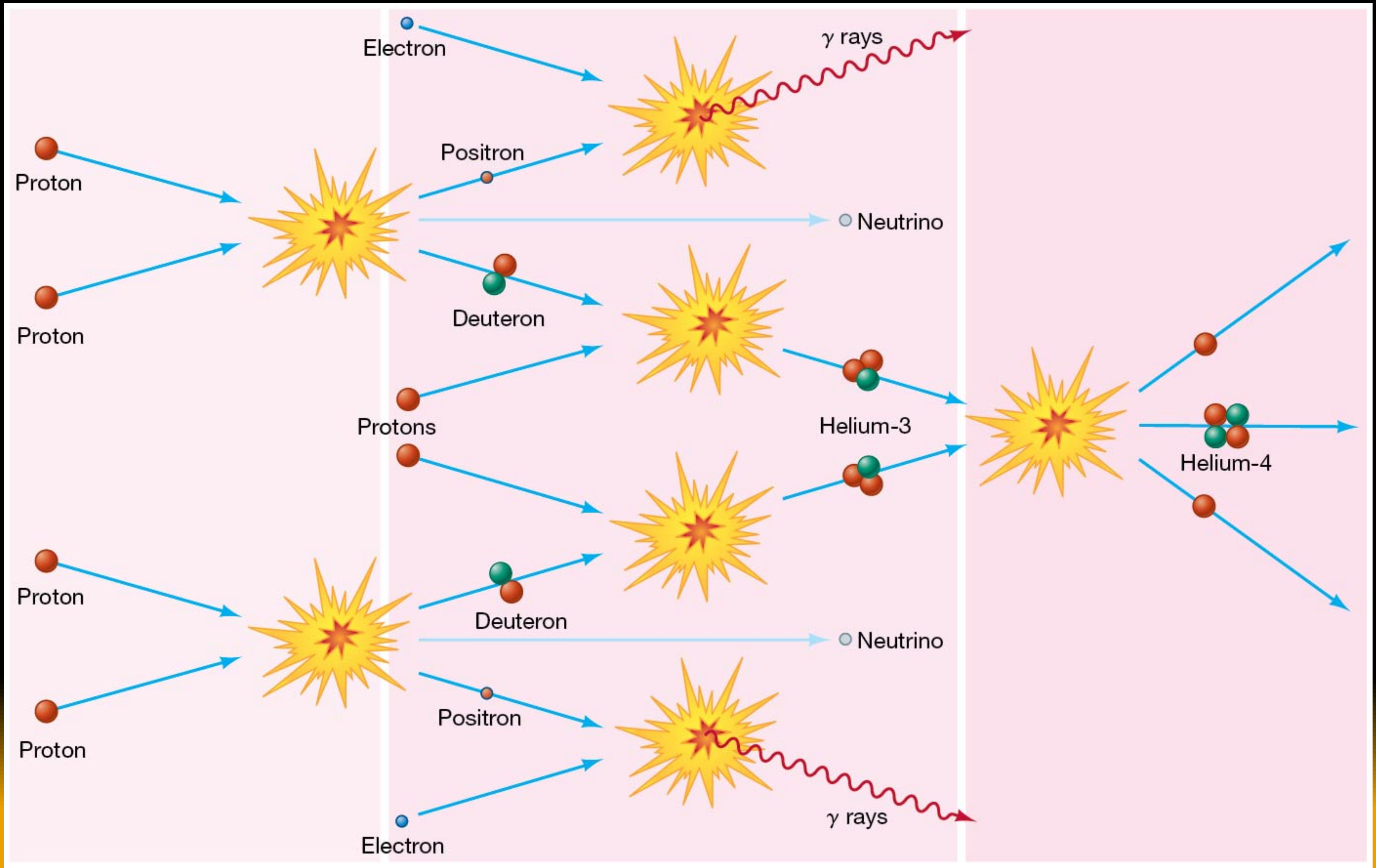
— The positron is the positively charged antiparticle of an electron. Anti-particles (which makes up anti-matter) are identical to those of a normal particle, except for the opposite charge. Particles and antiparticles annihilate (destroy) one another when they meet, *producing pure energy* in the form of gamma-ray photons.

— The neutrino is a chargeless and virtually massless elementary particle. (The name derives from the Italian for "little neutral one.") Neutrinos move at *nearly the speed of light* and interact with hardly anything. They can penetrate, without stopping, several light-years of lead. Their interactions with matter are governed by the weak nuclear force.



The Proton–Proton Chain in Detail

In the proton–proton chain, a total of six protons (and two electrons) are converted to two protons, one helium-4 nucleus, and two neutrinos. The two leftover protons are available as fuel for new proton–proton reactions, so the net effect is that four protons are fused to form one helium-4 nucleus. Energy, in the form of gamma rays, is produced at each stage.



Summary of the Sun's Energy Consumption

To fuel the Sun's present energy output, hydrogen must be fused into helium in the core at a rate of 600 million tons per second - a lot of mass, but only a tiny fraction of the total amount available.

As we will see in Chapter 12, the Sun will be able to sustain this rate of core burning for about another 5 billion years.

The energy eventually leaves the solar photosphere mainly in the form of visible and infrared radiation.

A comparable amount of energy is carried off by the neutrinos, which escape unhindered into space at almost the speed of light.

Telescopes Re-Visited:
Neutrino Telescopes

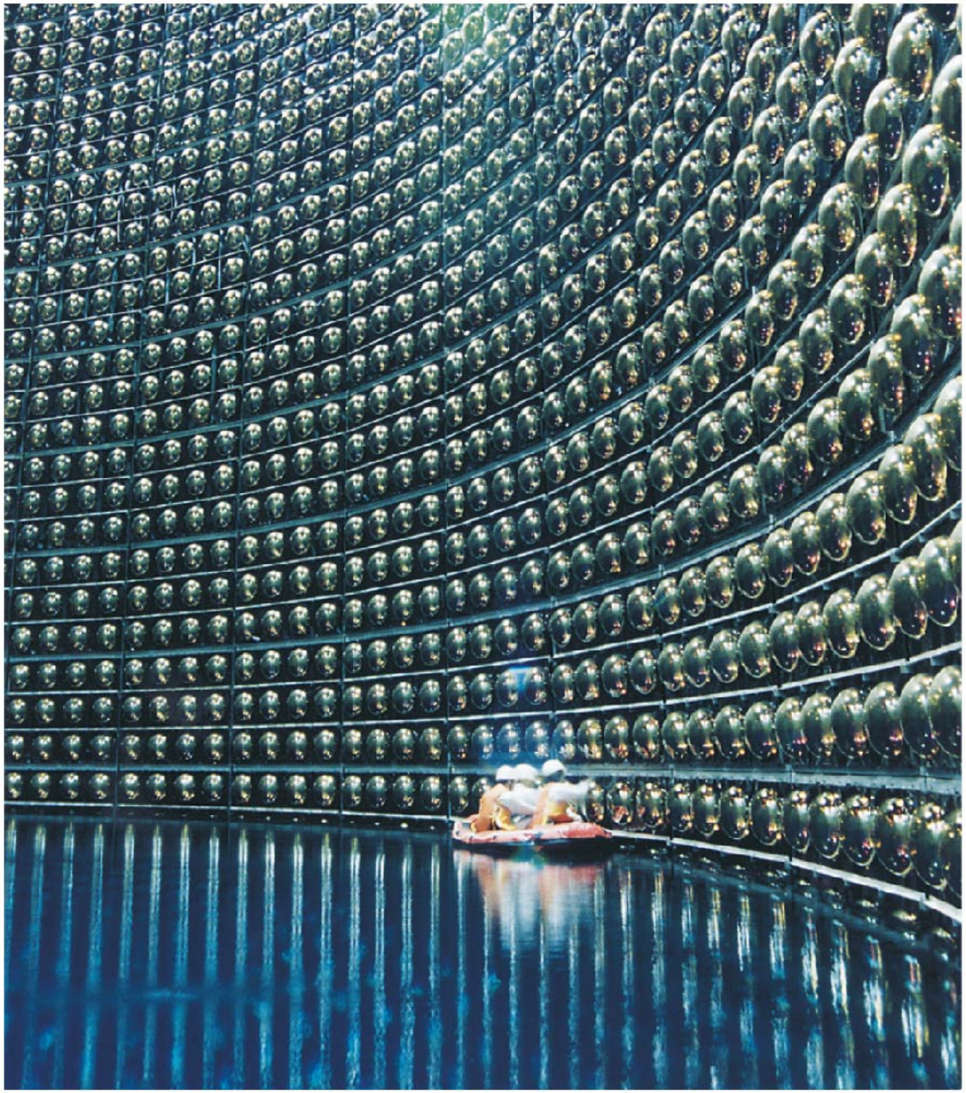
Neutrino 'Telescopes'

Neutrinos fly through all matter with only the occasional collision.

This swimming pool–sized "neutrino telescope" is buried beneath a mountain near Tokyo, Japan.

Called Super Kamiokande, it is filled with 50,000 tons of purified water hoping to spark a collision

It contains 13,000 individual light detectors to sense the telltale signature - a brief burst of light - of a neutrino passing through the apparatus.



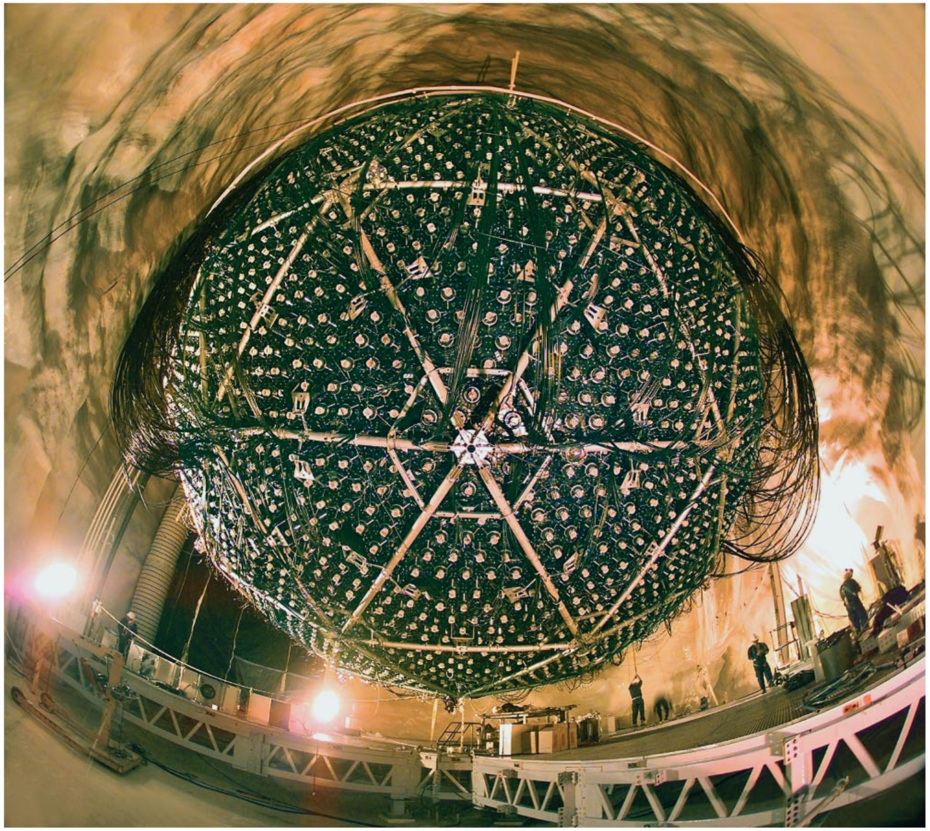
(a)

Neutrino Telescopes

The Sudbury Neutrino Observatory (SNO), situated 2 km underground in Ontario, Canada,

This is similar in design to the Kamiokande device, but, by using "heavy" water (with hydrogen replaced by deuterium water D_2O instead of ordinary water H_2O), and adding 2 tons of salt, it also becomes sensitive to other neutrino types.

The device contains 10,000 light-sensitive detectors arranged on the inside of the large sphere shown here.



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Neutrino Telescopes

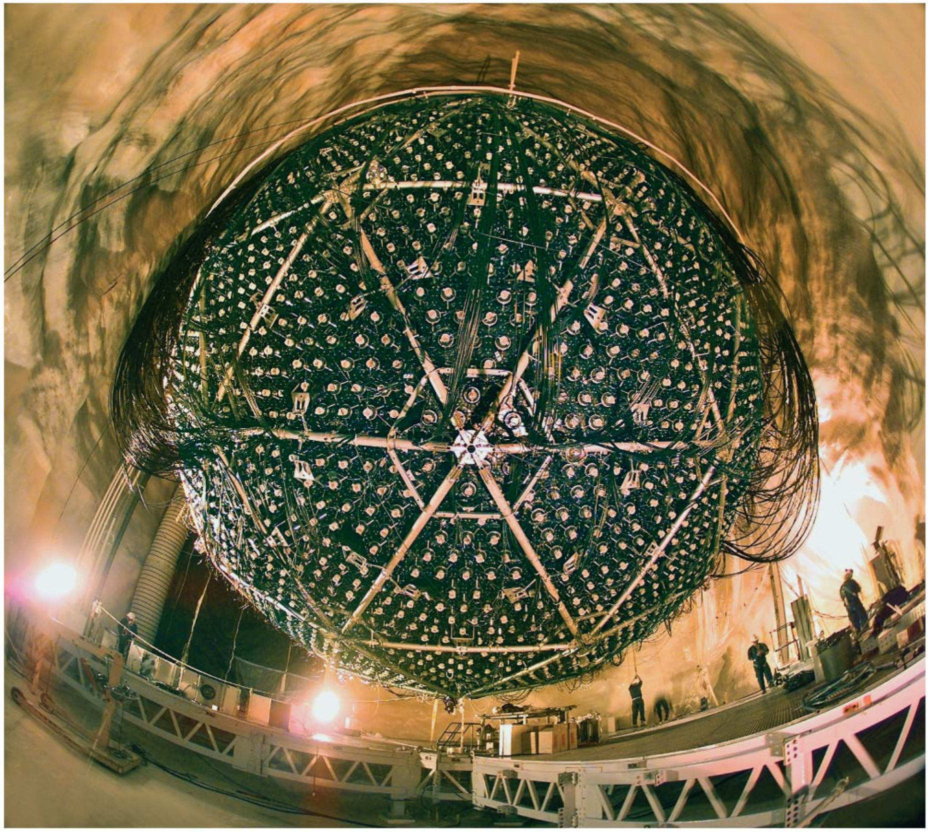
The Neutrino Problem - the total numbers of neutrinos observed from the Sun were *not consistent* with the standard solar model

In 2001, measurements made at the SNO revealed strong evidence for "other" neutrinos into which the Sun's neutrinos have been transformed.

Subsequent SNO observations confirmed the result.

Now the total numbers of neutrinos observed are *completely consistent* with the standard solar model.

The solar neutrino problem has been solved - and neutrino astronomy claimed its first major triumph!



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