15. Our Star

I say Live, Live, because of the Sun,
The dream, the excitable gift.

Anne Sexton (1928 – 1974)
American poet

Goodbye my friend it’s hard to die
When all the birds are singing in the sky
Now that the spring is in the air
Pretty girls are everywhere
Think of me and I’ll be there

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We had seasons in the sun

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Terry Jacks 1973

Agenda

- Projects due/start week from Thursday
- Will cover Ch. 16 starting Thursday (take quiz)
- Observations (Wed nights)
- Ch. 15—Our Sun

15.1 Why Does the Sun Shine?

Our goals for learning:

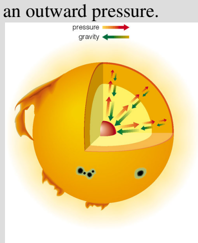
- What process creates energy in the Sun?
- Why does the Sun’s size remain stable?
- How did the Sun become hot enough for fusion in the first place?

The Sun’s Energy Source

- The first scientific theories involved chemical reactions or gravitational collapse.
  - chemical burning ruled out…it can not account for the Sun’s luminosity
  - conversion of gravitational potential energy into heat as the Sun contracts would only keep the Sun shining for 25 million years
  - late 19th-century geological research indicated the Earth was older than that
- Development of nuclear physics led to the correct answer
  - the Sun generates energy via nuclear *fusion* reactions
  - Hydrogen is converted into Helium in the Sun’s core
  - the mass lost in this conversion is transformed into energy
  - the amount of energy is given by Einstein’s equation: $E = mc^2$
  - given the Sun’s mass, this will provide enough energy for the Sun to shine for 10 billion years

Striking a Balance

- The Sun began as a cloud of gas undergoing gravitational collapse.
  - the same heating process, once proposed to power the Sun, did cause the core of the Sun to get hot & dense enough to start nuclear fusion reactions
- Once begun, the fusion reactions generated energy which provided an outward pressure.



- This pressure perfectly balances the inward force of gravity.
  - deep inside the Sun, the pressure is strongest where gravity is strongest
  - near the surface, the pressure is weakest where gravity is weakest
- This balance is called **gravitational equilibrium**.
  - it causes the Sun's size to remain stable

15.2 Plunging to the Center of the Sun: An Imaginary Journey

Our goals for learning:

- What are the major layers of the Sun, from inside out?
- What do we mean by the "surface" of the Sun?
- What is the Sun made of ?

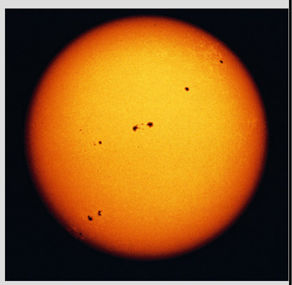
Basic Properties of the Sun

Distance: 1.48×10^8 km = 1 A.U.

Mass: 1.99×10^{30} kg

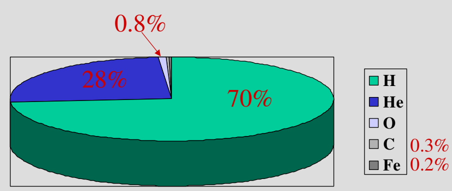
Radius: 6.96×10^5 km

Density: 1.41 g/cm^3



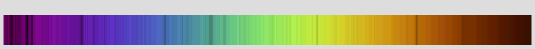
Luminosity: 3.8×10^{26} watts

Composition of the Sun



Composition of the Sun

We know this by identifying the **absorption lines** in the Sun's spectrum.

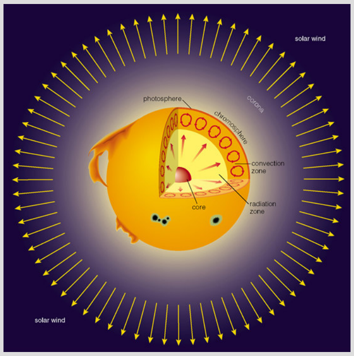


These lines are formed in the photosphere.

Layers of the Sun

	Temperature	Depth
Core	1.5×10^7 K	0.25 $R_\odot$
Radiation Zone	> 2×10^6 K	0.70 $R_\odot$
Convection Zone	< 2×10^6 K	0.85 $R_\odot$
Photosphere	5.8×10^3 K	400 km thick
Chromosphere	1– 5 $\times 10^4$ K	2,500 km thick
Corona	2×10^6 K	600,000 km thick
Solar Wind	> 10^6 K	beyond the orbit of Pluto

Layers of the Sun



Core

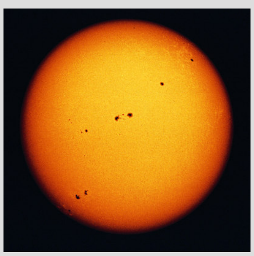
- T = 1.5×10^7 K; depth = 0 – 0.25 $R_\odot$
- This is where the Sun’s energy is generated.

Interior Zones

- T < 8×10^6 K; depth = 0.25 – 0.86 $R_\odot$
- Energy is transported through the interior.
- The interior is divided into two zones:
  - Radiation Zone
  - Convection Zone
- Boundary between them is at:
  - T = 2×10^6 K; depth = 0.70 $R_\odot$

Photosphere

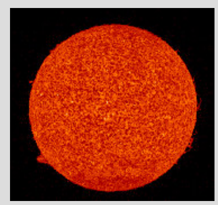
- T = 5,800 K; depth = 400 km
- This is the yellow “surface” that we see.



Chromosphere

- T = 1 – 5 x 10^4 K; depth = 2,500 km
- A thin layer above the photosphere where most of the Sun’s UV light is emitted.

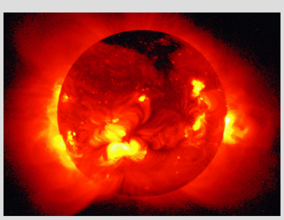
- UV image of the Sun
- light emitted from neutral Helium at 20,000 K



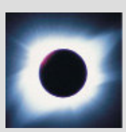
courtesy of SOHO/SUMER consortium
SOHO is a project of ESA and NASA

Corona

- T = 2×10^6 K; depth ≈ 600,000 km
- The hot, ionized gas which surrounds the Sun.
  – it emits mostly X-rays
- It can be seen in visible light during an eclipse.



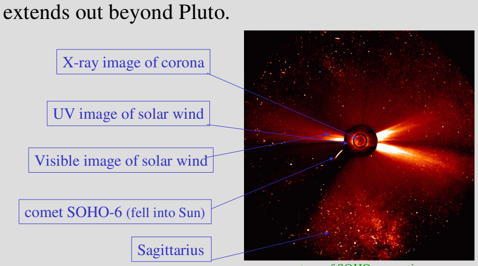
X-ray image (YOHKOH telescope)



Visible image

Solar Wind

- The stream of electrons, protons, Helium nuclei and other ions which flow out from the Sun.
- It extends out beyond Pluto.



courtesy of SOHO consortium
SOHO is a project of ESA & NASA

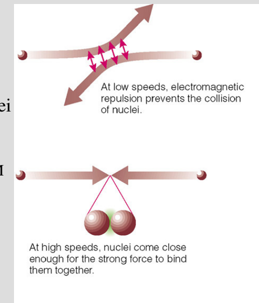
15.3 The Cosmic Crucible

Our goals for learning:

- Why does fusion occur in the Sun's core?
- Why is energy produced in the Sun at such a steady rate?
- Why was the Sun dimmer in the distant past?
- How do we know what is happening inside the Sun?
- What is the Solar neutrino problem? Is it solved?

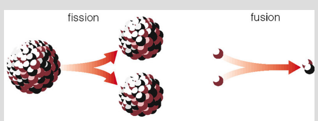
Why does fusion occur in the Sun's core ?

- Nuclear fusion
  - a reaction where heavier nuclei are created by combining (*fusing*) lighter nuclei.
  - all nuclei are positively charged
- Electromagnetic force causes nuclei to repel each other.
  - for fusion to occur, nuclei must be moving fast enough to overcome E-M repulsion
  - this requires high temperatures & pressures
- When nuclei touch, the nuclear force binds them together



What is nuclear fission ?

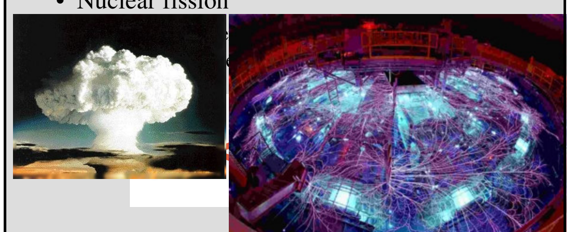
- Nuclear fission
  - a reaction where lighter nuclei are created by splitting heavier nuclei.



Only fission has been achieved by mankind
It is easier to destroy than to create.

What is nuclear fission ?

- Nuclear fission



~~Only fission has been achieved by mankind~~
~~It is easier to destroy than to create.~~

Neutrons

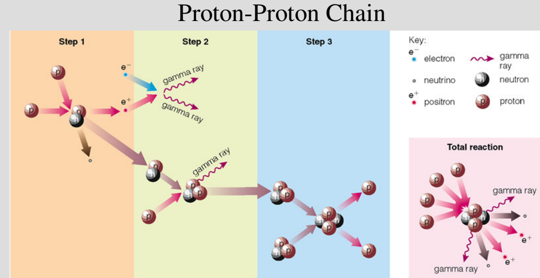
Neutrons are not stable! They do not exist alone for long!

$n \longrightarrow p^+ + e^- + \bar{\nu}_e$ (β-decay)

$p^+ \longrightarrow n + e^+ + \nu_e$ (inverse β-decay)

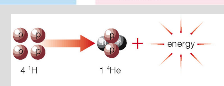
ν_e is a **neutrino** – a weakly interacting particle which has almost no mass and travels at nearly the speed of light.

Proton-Proton Chain



IN: 6 H, (2 e^-)
OUT: He, 2 H, 2 ν_e, 4 γ

Effectively 4 H nuclei are converted into 1 He nucleus and energy is released.



Why does the Sun Shine ?

But….

mass of He = 99.3% of 4 x mass of H

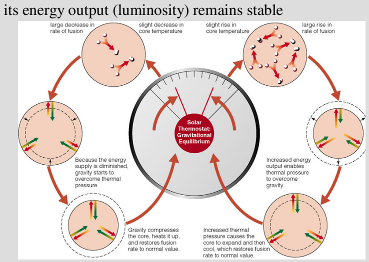
where did the .007 (4 m_H) go?

into energy!!!

$$E = mc^2$$

The Solar Thermostat

- The rate of fusion reactions depends on temperature.
  - the higher the T, the faster the rate, the more energy is produced
- This fact, coupled with gravitational equilibrium, acts as a mechanism which regulates the Sun’s energy output.
  - its energy output (luminosity) remains stable

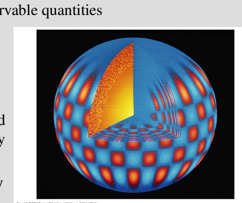


The Solar Luminosity

- The Sun’s luminosity is stable over the short-term.
- However, as more Hydrogen fuses into Helium:
  - four H nuclei convert into one He nucleus
  - the number of particles in Sun’s core *decreases* with time
  - the Sun’s core will contract, causing it to heat up
  - the fusion rate will increase to balance higher gravity
  - a new *equilibrium* is reached for stability at a higher energy output
  - the Sun’s luminosity increases with time over the long-term
- Models indicate the Sun’s luminosity has increased 30% since it formed 4.6 billion years ago.
  - it has gone from 2.9 x 10^{26} watts to today’s 3.8 x 10^{26} watts

“Observing” the Solar Interior

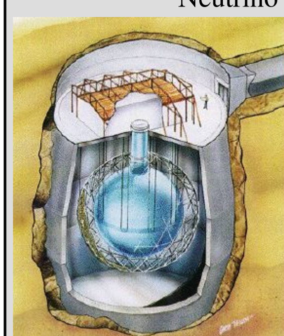
- The Sun’s interior is opaque…
  - we can not see directly into it with light
- We can construct mathematical computer models of it.
  - the models are a grid of temperature, pressure, & density vs. depth
  - these values are calculated using known laws of physics
  - they are tested against the Sun’s observable quantities
- We can directly measure sound waves moving through the interior
  - we observe “sunquakes” in the photosphere by using Doppler shifts
  - motion of sound waves can be checked against interior conditions predicted by models
- There is another way to see directly into the core…**neutrinos**!

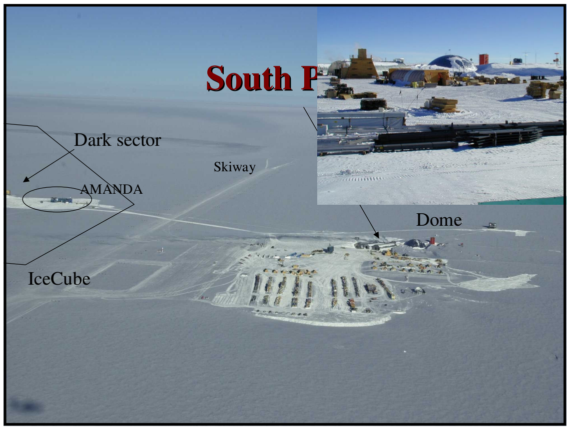


The Neutrino Problem

- Neutrinos come to us directly from the core of the Sun, a product of the proton-proton chain.
- We have detected them, proving that the theory of nuclear fusion reactions is correct!
- But we only detect about 30% - 50% of the neutrinos which are predicted by theoretic models.
  - either our understanding of nuclear fusion reactions or our understanding of neutrinos is wrong!
- We have since discovered three types of neutrinos:
  - electron (ν_e), muon (ν_μ), and tau (ν_τ)
  - our neutrino detectors can register only electron neutrinos
- If neutrinos can change type after being created, this could solve the “neutrino problem.”

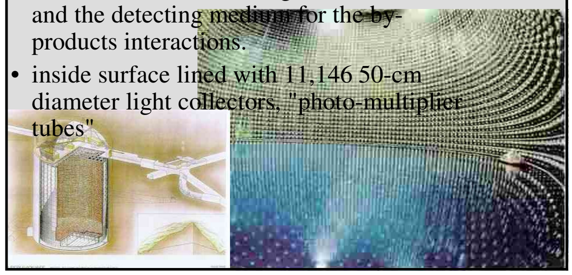
Neutrino Detectors





Super-Kamiokande

- 50,000 ton tank of water
- located 1 km underground
- water acts as both the target for neutrinos, and the detecting medium for the by-products interactions.
- inside surface lined with 11,146 50-cm diameter light collectors, "photo-multiplier tubes"



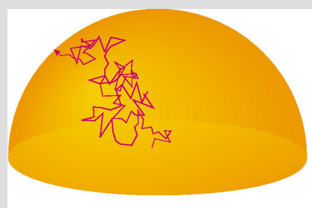
15.4 From Core to Corona

Our goals for learning:

- How long ago did fusion generate the energy we now receive as sunlight?
- How are sunspots, prominences, and flares related to magnetic fields?
- What is surprising about the temperature of the chromosphere and corona, and how do we explain it?

Methods of Energy Transport

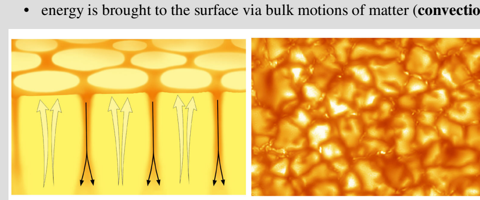
- Radiation Zone
  - energy travels as photons of light, which continually collide with particles
  - always changing direction (*random walk*), photons can change wavelengths
  - this is called **radiative diffusion**



- This is a slow process!
- It takes about 1 million years for energy to travel from the core to the surface.

Methods of Energy Transport

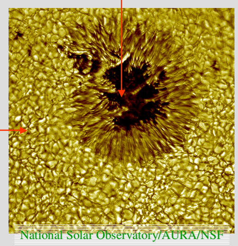
- Convection zone
  - photons arriving at bottom of convection zone are absorbed instead of scattered by matter
  - the bottom of the zone is heated … hot gas rises to the top
  - cooler gas sinks to the bottom…just like when you boil a pot of water!
  - energy is brought to the surface via bulk motions of matter (**convection**)



Photospheric Features

Sunspots: dark spots on the surface where the temperature is cooler.

Granulation: the tops of convection cells seen "bubbling" on the Solar surface



National Solar Observatory/AURA/NSF

Sunspots

courtesy of SOHO/MDI consortium
SOHO is a project of ESA and NASA

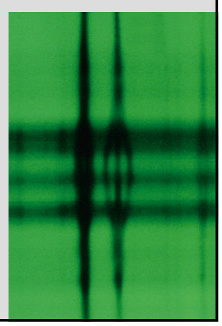
Movie. Click to play.

Sunspots occur in pairs; the pairs cluster into groups; and they rotate with the Sun

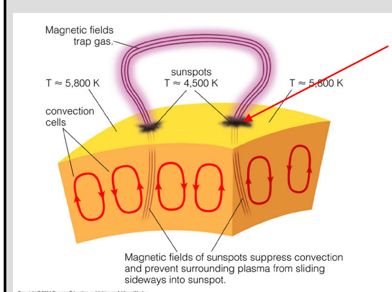
Sunspots come and go over an 11-year cycle.

What causes Sunspots?

- The answer is in their spectra.
- Absorption lines are split in three.
- This *Zeeman Effect* is evidence of strong **magnetic fields**.



What causes a sunspot?



magnetic field slows down convection;
Less heat is transported to surface;
so that part of photosphere is cooler

Coronal Features

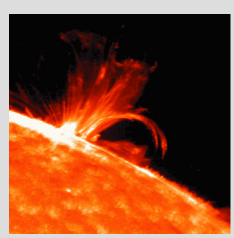
Prominences – gas trapped in the magnetic fields is heated and elevated through the chromosphere to the corona

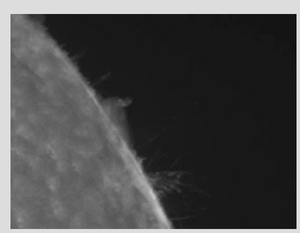
X-ray images from NASA's TRACE mission.

Movie. Click to launch.

Coronal Features

Flares – when a magnetic loop breaks, it releases matter and energy into space



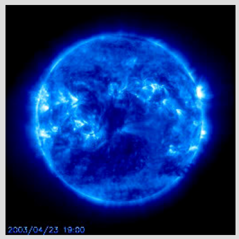


Movie. Click to play.

X-ray images from NASA's TRACE mission.

The Corona

- Magnetic loops are shaken at their bases by turbulent motions in the convection zone.
- Kinked, twisted magnetic field loops release energy to heat gas to 2 million K.
- The charged gas (ions) remains stuck to the magnetic loops.
- The corona is not uniform; there are empty patches called **coronal holes**
- Magnetic heating explains why temperatures start to increase above the photosphere.



Movie. Click to play.

courtesy of SOHO/EIT consortium
SOHO is a project of ESA and NASA

15.5 Solar Weather and Climate

Our goals for learning:

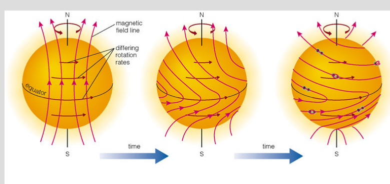
- Describe the sunspot cycle.
- What effect does Solar activity have on Earth and its inhabitants?

Differential Rotation

The Sun does not rotate as a solid body (like the Earth.) The equator rotates faster than the poles.

Period of Rotation:

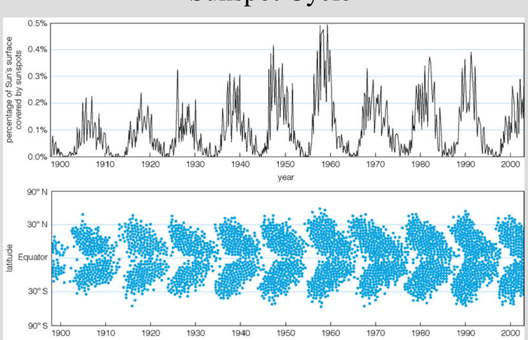
25 days (equator)
30 days (poles)



Solar Activity

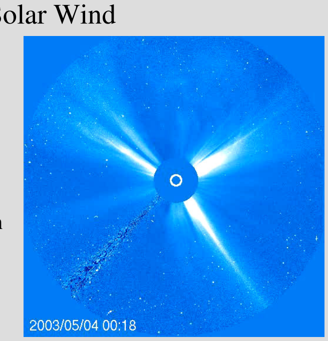
- The photosphere of the Sun is covered with sunspots.
- Sunspots are not constant; they appear & disappear.
- They do so in a cycle.
- It repeats every 11 yrs.
  - Sun's magnetic field switches polarity every 11 yrs
  - so the entire cycle repeats every 22 yrs

Sunspot Cycle



Solar Wind

- When magnetic field lines break, they release the charged particles into space.
- This so-called **solar wind** escapes through the coronal holes.

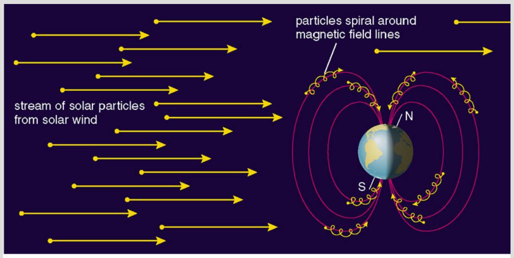


courtesy of SOHO/LASCO consortium
SOHO is a project of ESA and NASA

Movie. Click to play.

Solar Wind

electrons, protons, He nuclei expelled by flares



Interact with Earth's magnetic field to cause…

The Aurorae

the Northern & Southern Lights

- A strong Solar wind can affect human technology by:
  - interfering with communications
  - knocking out power grids
  - damage electronics in space vechicles
- We are not yet sure of the effect which Solar activity has on Earth's climate.

What have we learned?

- What process creates energy in the Sun?
  - Fusion of hydrogen into helium in the Sun's core generates the Sun's energy.
- Why does the Sun's size remain stable?
  - The Sun's size remains stable because it is in gravitational equilibrium—the outward pressure of hot gas balances the inward force of gravity at every point within the Sun.
- How did the Sun become hot enough for fusion in the first place?
  - As the Sun was forming, it grew hotter as it shrank in size because gravitational contraction converted gravitational potential energy into thermal energy. Gravitational contraction continued to shrink the Sun and to raise its central temperature until the core became hot and dense enough for nuclear fusion.

What have we learned?

- What are the major layers of the Sun, from inside out?
  - Core, radiation zone, convection zone, photosphere, chromosphere, and corona.
- What do we mean by the "surface" of the Sun?
  - We consider the photosphere to be the surface of the Sun because light can pass through the photosphere but cannot escape from deeper inside the Sun. Thus, photographs of visible light from the Sun show us what the photosphere looks like.
- What is the Sun made of?
  - It is made almost entirely (98%) of hydrogen and helium.

What have we learned?

- Why does fusion occur in the Sun's core?
  - The core temperature and pressure are so high that colliding nuclei can come close enough together for the strong force to overcome electromagnetic repulsion and bind them together.
- Why is energy produced in the Sun at such a steady rate?
  - The fusion rate is self-regulating like a thermostat. If the fusion rate increases for some reason, the added energy production puffs up and cools the core, bringing the rate back down. Similarly, a decrease in the fusion rate would allow the core to shrink and heat, bringing the fusion rate back up.

What have we learned?

- Why was the Sun dimmer in the distant past?
  - Although the fusion rate is steady on short time scales, the fusion rate gradually increases over billions of years, increasing the Sun's luminosity. The increase occurs because fusion gradually reduces the number of individual nuclei in the solar core — because 4 hydrogen nuclei are fused to make just 1 helium nucleus — which causes the core to shrink and become hotter.
- How do we know what is happening inside Sun?
  - We can construct theoretical models of the solar interior using known laws of physics, and check the models against observations of the Sun's output and studies of "sun quakes" and of solar neutrinos.

What have we learned?

- What is the solar neutrino problem? Is it solved?
  - Since the 1960s, special neutrino detectors captured fewer neutrinos coming from the Sun than models of fusion in the core predicted. This was a problem because it meant that something must be wrong either with our understanding of nuclear fusion in the Sun or of our understanding of neutrinos. The problem now appears to be solved. Apparently, neutrinos can transform themselves among three different types as they travel from the solar core to Earth, while most detectors can capture only one type. Thus, the detectors capture less than the expected number of neutrinos because some of the neutrinos produced in the Sun transform into other types before they reach Earth.

What have we learned?

- How long ago did fusion generate the energy we now receive as sunlight?
  - Fusion created the energy we receive today about a million years ago. This is the time it takes for photons and then convection to transport energy through the solar interior to the photosphere. Once sunlight emerges from the photosphere, it takes only about 8 minutes to reach Earth.

What have we learned?

- How are sunspots, prominences, and flares related to magnetic fields?
  - Sunspots occur where strong magnetic fields trap and isolate gas from the surrounding plasma of the photosphere. The trapped gas cools, so that sunspots became cooler and darker than the rest of the photosphere. Sunspots therefore tend to occur in pairs connected by a loop of magnetic field, which may rise high above the surface as a solar prominence. The magnetic fields are twisted and contorted by the Sun's differential rotation, and solar flares may occur when the field lines suddenly snap and release their energy.

What have we learned?

- What is surprising about the temperature of the chromosphere and corona, and how do we explain it?
  - Temperature gradually decreases from the core to the photosphere, but then rises back up in the chromosphere and corona. These high layers of the Sun are probably heated by energy carried upward along the magnetic field lines by waves generated as turbulent motions in the convection zone shake the magnetic field lines..

What have we learned?

- Describe the sunspot cycle.
  - The sunspot cycle, or the variation of the number of sunspots on the Sun's surface, has an 11 year period. The magnetic field flip-flops every 11 years, for a 22 year magnetic cycle. Sunspots first appear at mid-latitudes at solar minimum, then become increasingly more common near the Sun's equator as the next minimum approaches.
- What effect does solar activity have on Earth and its inhabitants?
  - Particles ejected from the Sun by solar flares and other types of solar activity can affect communications, electric power delivery, and the electronic circuits in space vehicles. It is not clear how solar activity affects the Earth's climate.

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4. Because gravitational force decreases with altitude.
5. At higher altitudes, faster moving molecules escape, thereby reducing the density of the gas.

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Which of the following can be used to directly measure the Sun's mass?

1. Solar luminosity and Earth-Sun distance.
2. Solar temperature and Earth-Sun distance.
3. Solar rotation rate and Earth-Sun distance.
4. Earth's mass and orbital period.
5. Venus-Sun distance and the length of a Venetian year.

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Is the number of solar neutrinos zipping through our bodies significantly lower at night?

1. Yes, the passage of *all* solar neutrinos through the Earth stops at night.
2. Yes, the passage of a significant number of solar neutrinos through the Earth stops at night.
3. No, the Earth is not thick enough to stop a significant number of solar neutrinos.
4. No, the number of solar neutrinos created by the Sun remains the same whether it's day or night.

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If fusion in the solar core ceased today, worldwide panic would break out tomorrow as the Sun would begin to grow dimmer.

1. Yes, because the Earth would quickly freeze over.
2. Yes, because the Earth would no longer be bound to the solar system and would drift into space.
3. Yes, because the Sun would collapse and the planets would soon follow.
4. No, it takes thousands of years for photons created in nuclear reactions at the solar core to reach the surface.
5. No, the Sun would continue to glow brightly for billions of years because of gravitational contraction.

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If you want to see a lot of sunspots, just wait for the time of solar maximum.

1. Yes, the number of sunspots peak at solar maximum.
2. No, the number of sunspots peak at solar minimum.
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