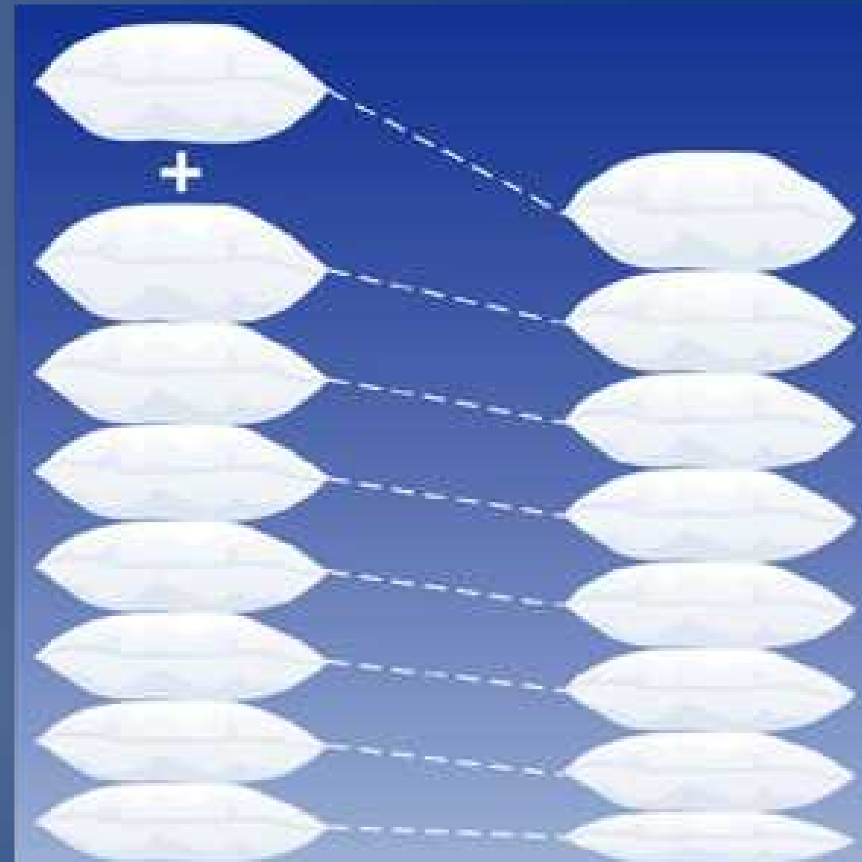
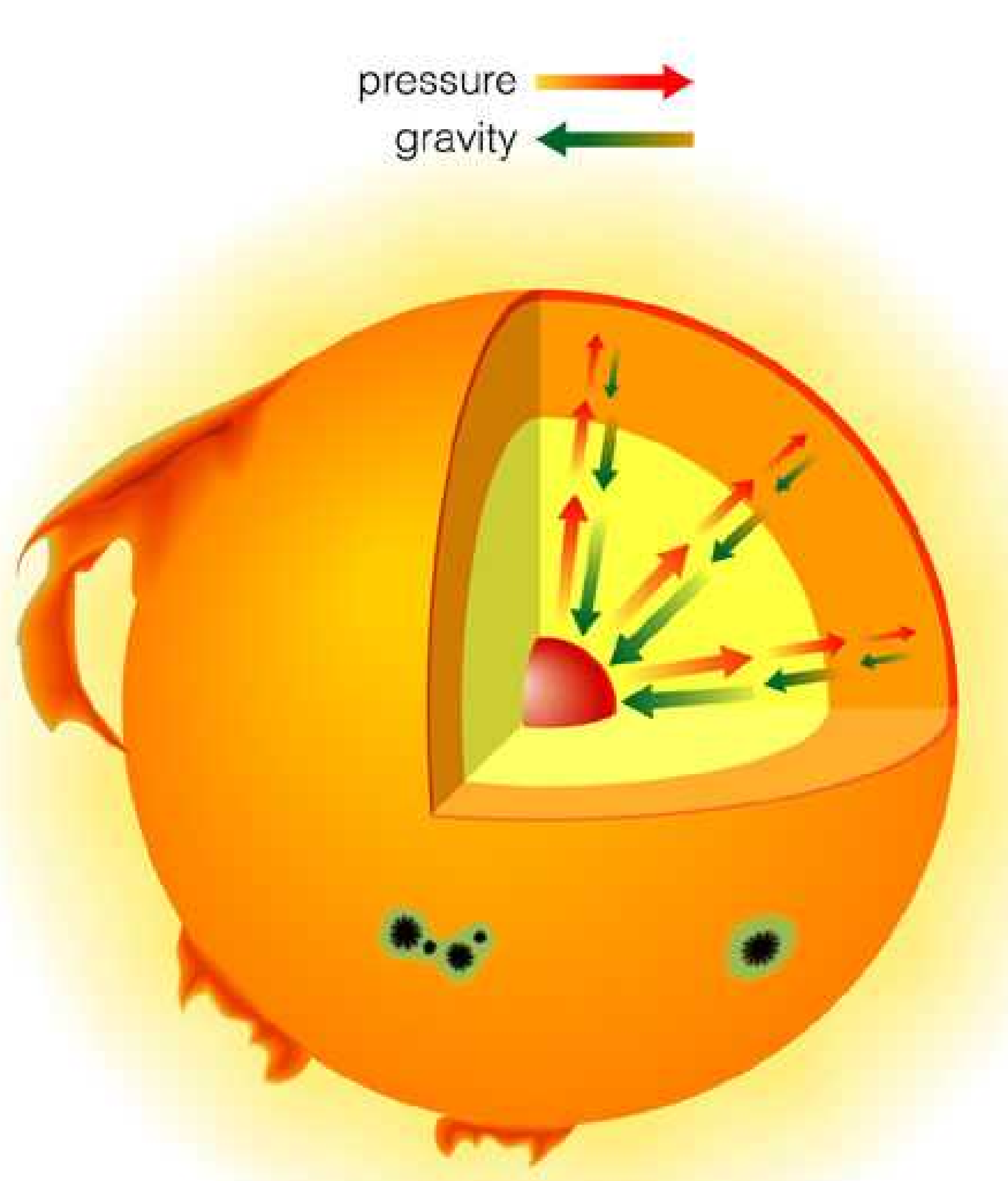
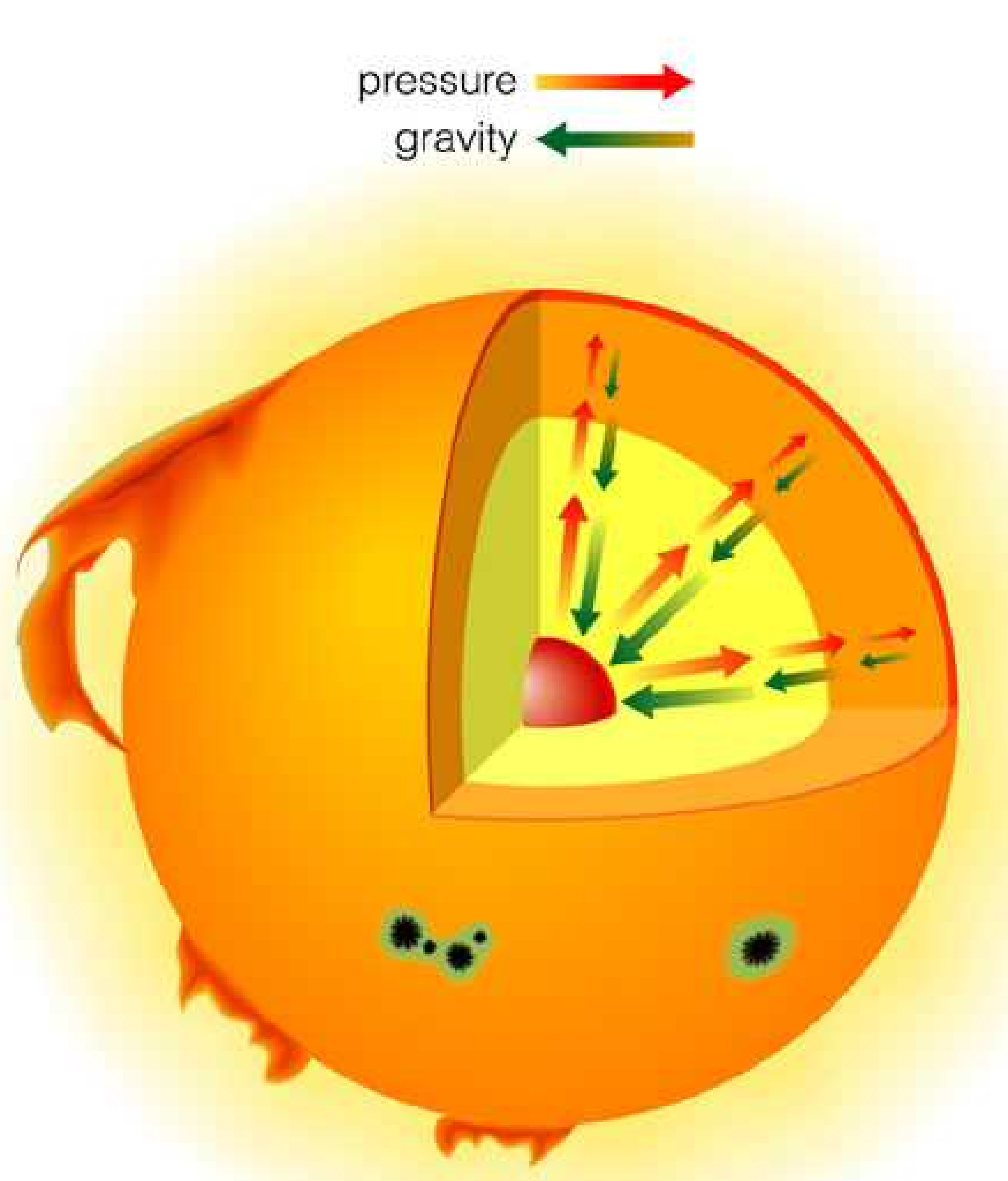


Weight of upper layers compresses
lower layers



Gravitational equilibrium:

Energy provided by fusion maintains the pressure



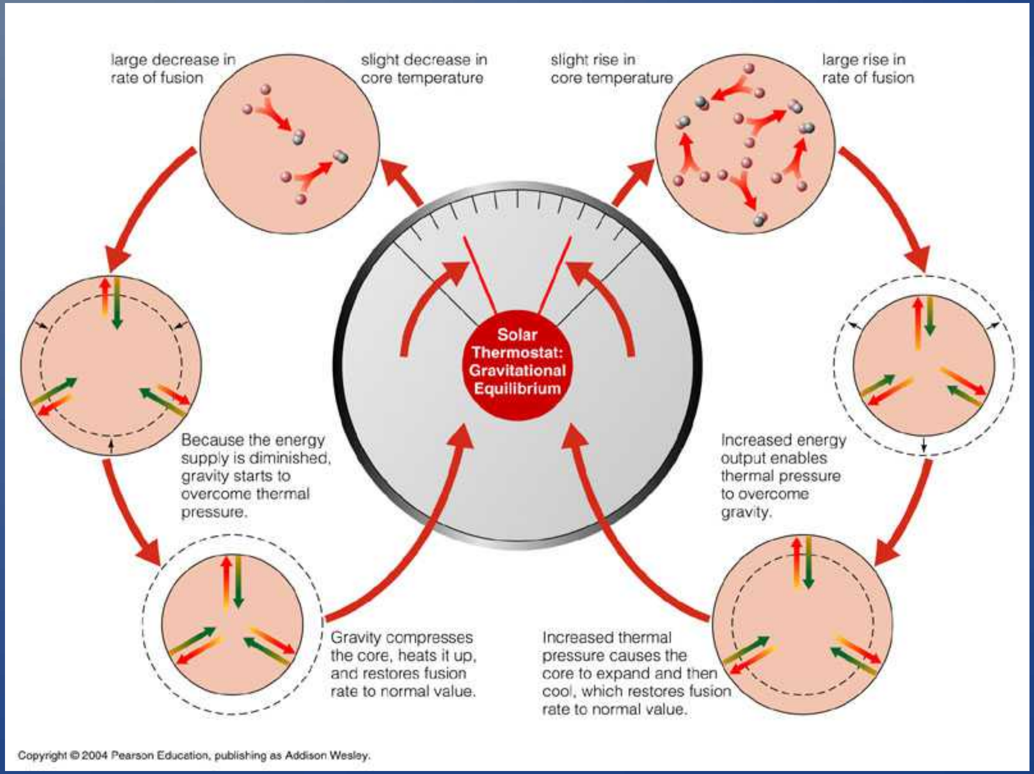
Gravitational contraction:

Provided energy that heated core as Sun was forming

Contraction stopped when fusion began

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

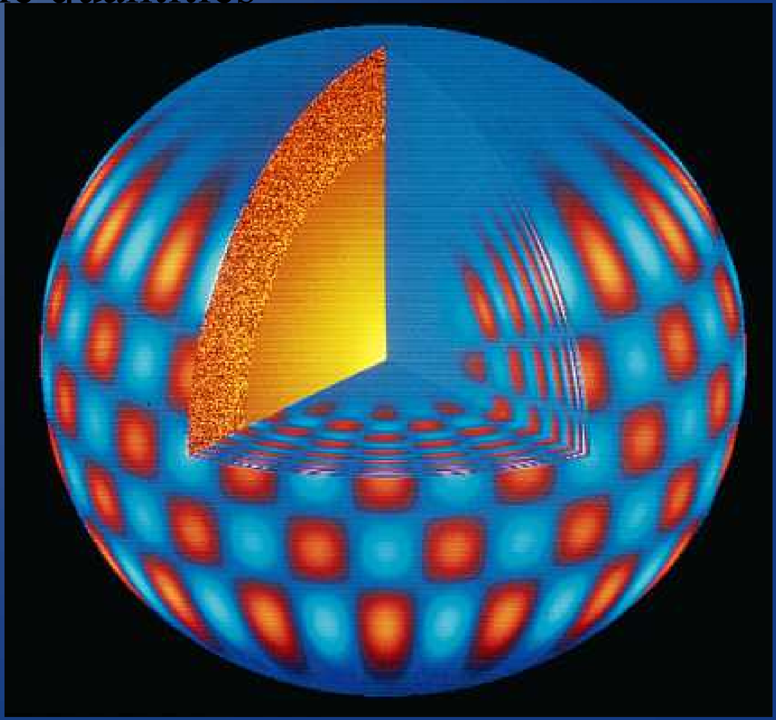


The Solar Luminosity

- 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 1026 watts to today's 3.8 x 1026 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**!



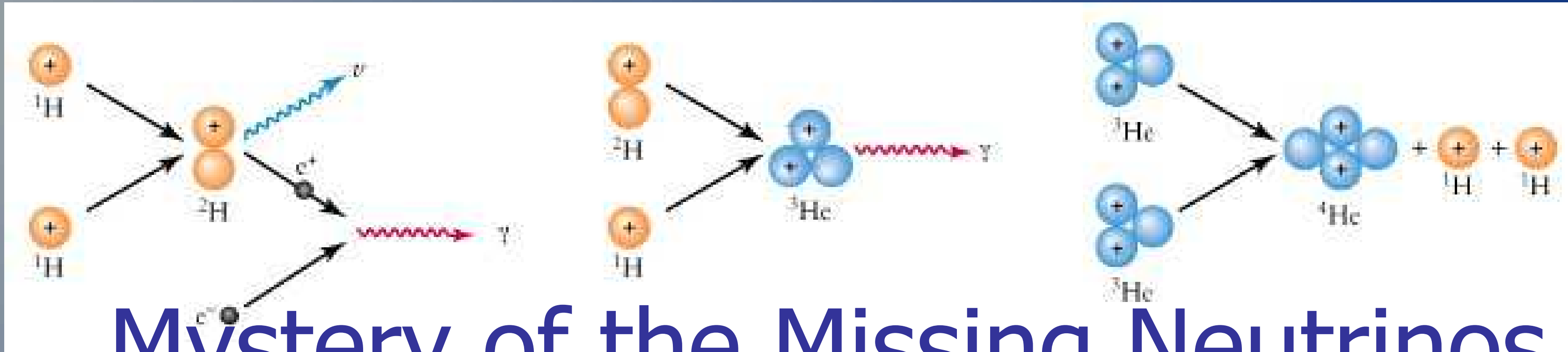
Aside: Neutrons

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

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

$p^{+} \longrightarrow n + e^{+} + \ e$ (inverse -decay

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



Mystery of the Missing Neutrinos

- models of the solar interior predicted that 1038 neutrinos were released every second
- Neutrino detectors on Earth watched for collisions between perchloroethylene (C2Cl4) and neutrinos which produces radioactive argon.
- Only 1/3 of the expected neutrinos from the Sun were being detected
- No one knew why this was happening

Mystery of the Missing Neutrinos

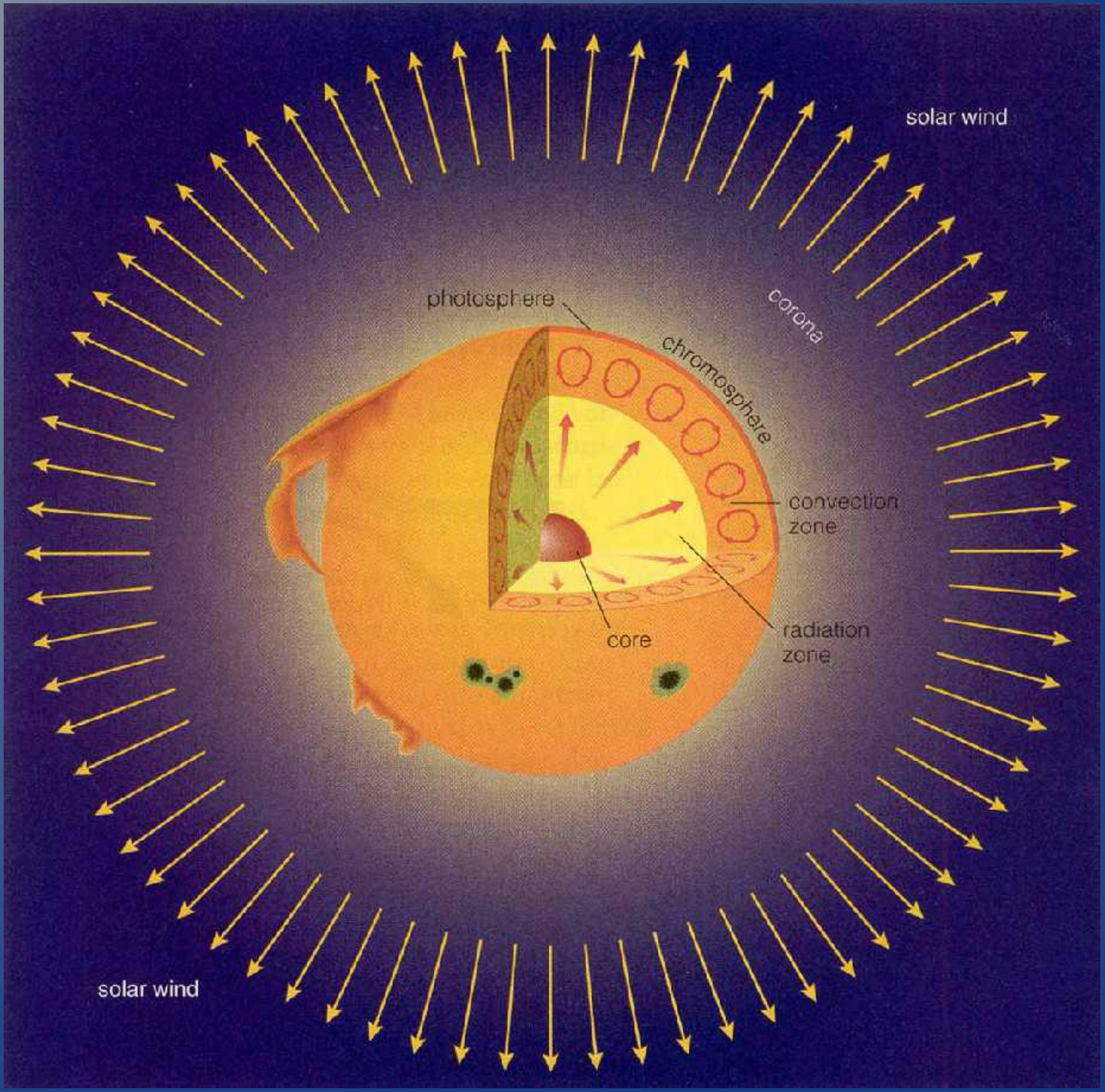
- But high energy physicists figured it out!
- Neutrinos change from one type to another.

$^{1}H + ^{1}H \Rightarrow ^{2}H + e^{+} + \nu_e$

electron (e), muon ( ), and tau ( )

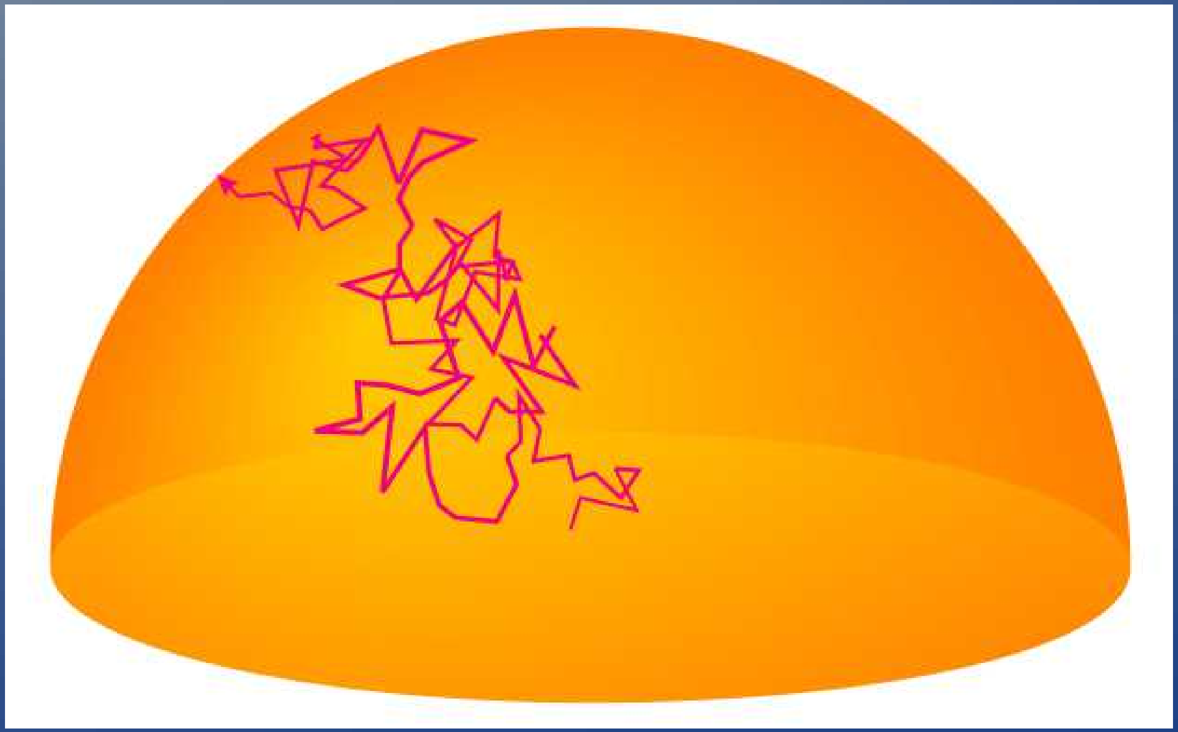
our neutrino detectors can register only electron neutrinos!!

Layers of the Sun



Methods of Energy Transport

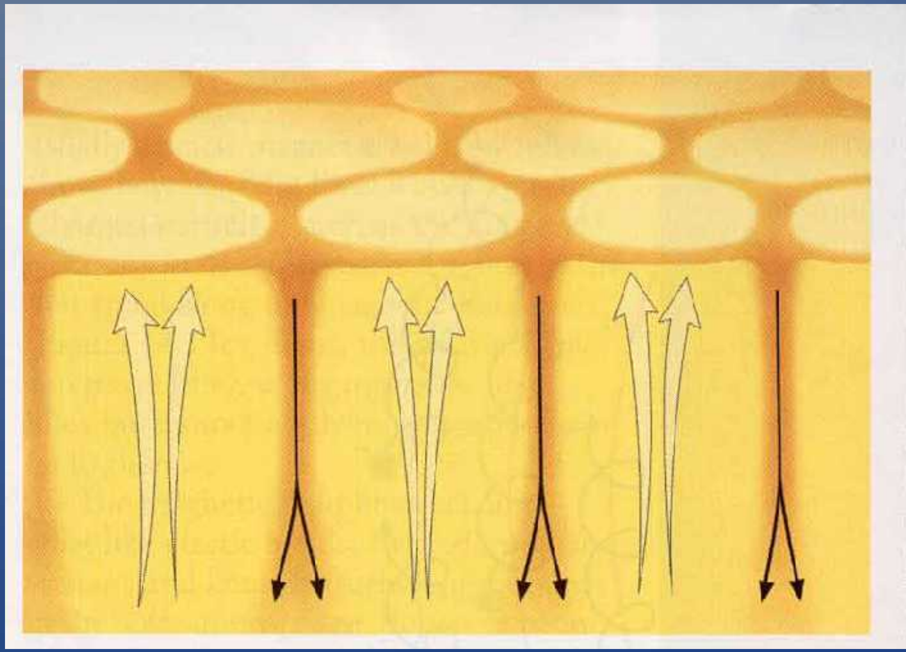
- Radiation Zone
  - energy travels as photons of light, which continually collide with particles
  - always changing direction (*random walk*), photons can change wavelengths
  - this is called **radiative diffusion**



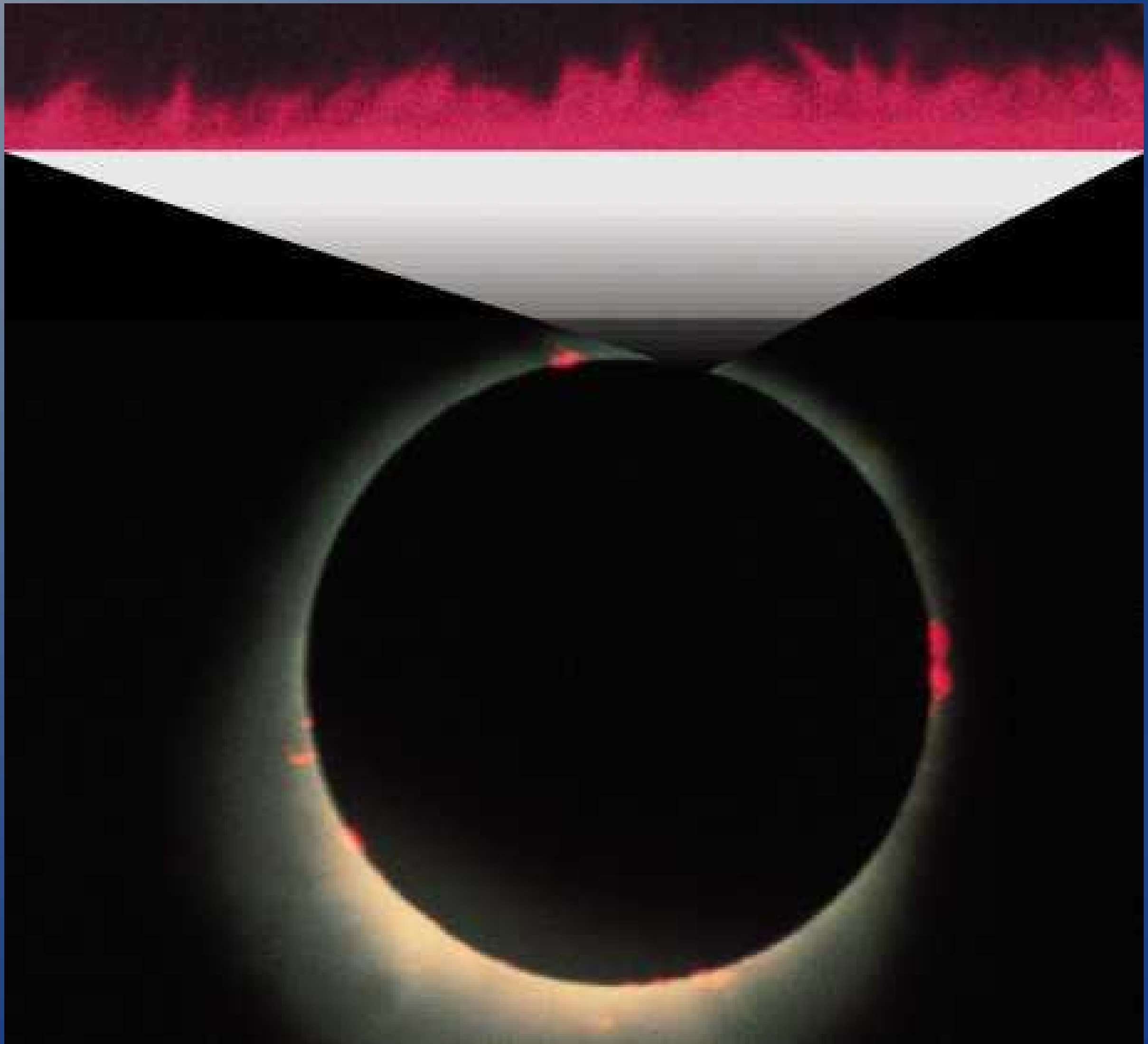
- This is a slow process!
- It takes about 1 million years for energy to travel from the core to the surface.

Methods of Energy Transport

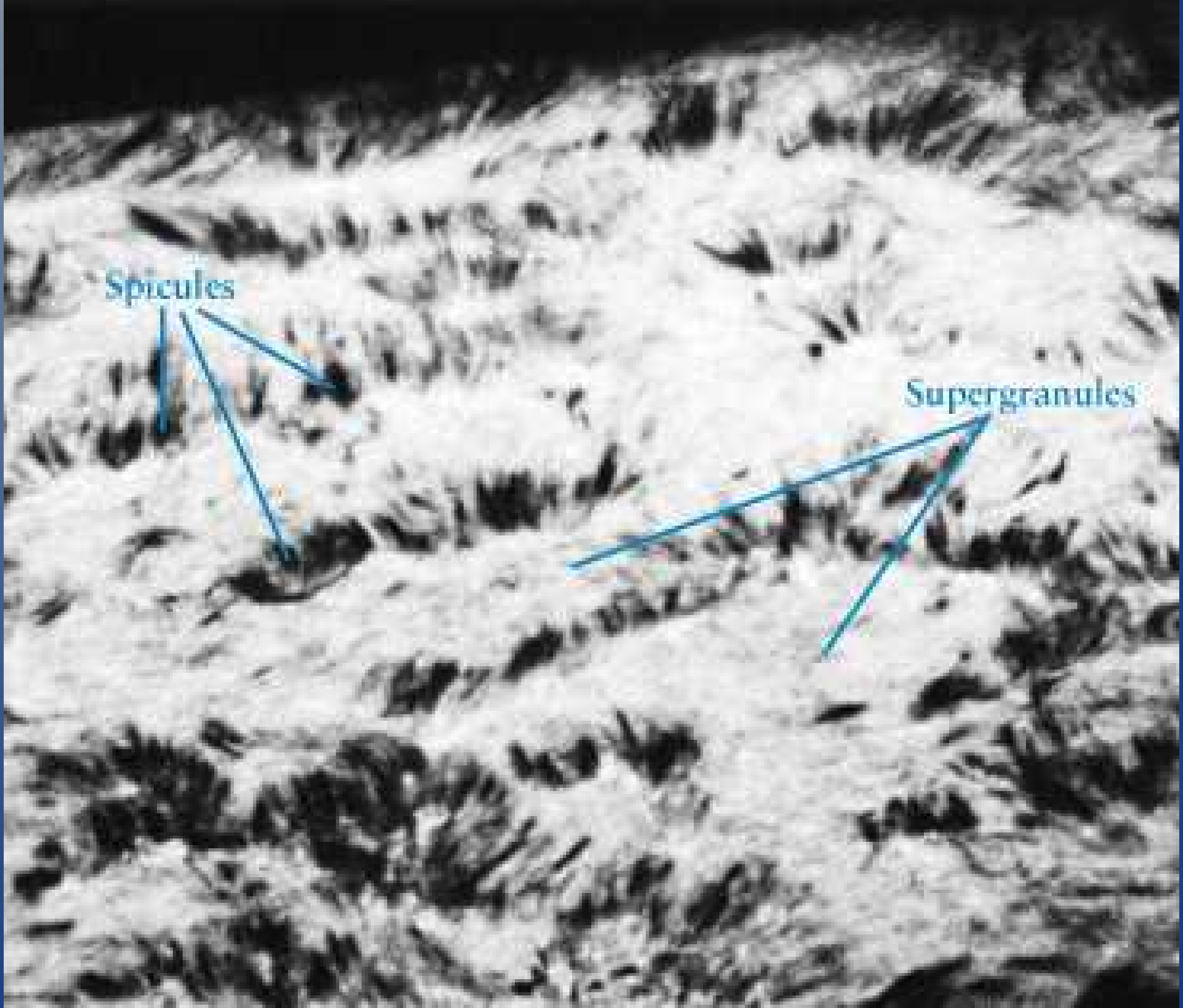
- Convection zone
  - photons arriving at bottom of convection zone are absorbed instead of scattered by matter
  - the bottom of the zone is heated … hot gas rises to the top
  - cooler gas sinks to the bottom…just like when you boil a pot of water!
  - energy is brought to the surface via bulk motions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



Above the photosphere, the ***chromosphere*** is characterized by spikes of gas called ***spicules***



Supergranuals surrounded by spicules



Chromosphere

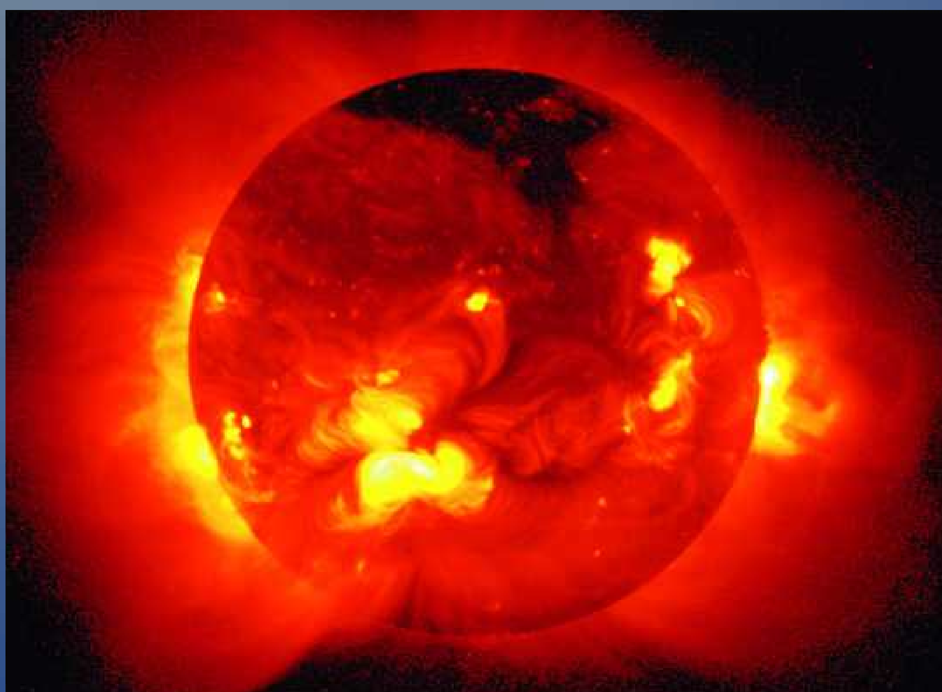
- T = 1 – 5 x 104 K; depth = 2,500 km
- A thin layer above the photosphere where most of the Sun’s UV light is emitted.

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

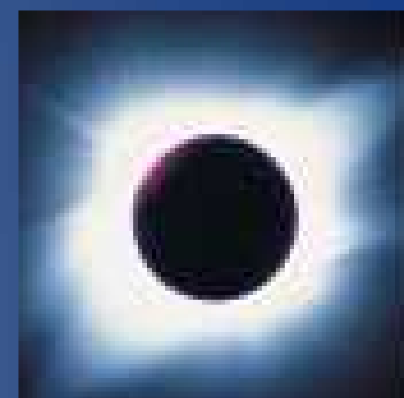
courtesy of SOHO/SUMER consortium
SOHO is a project of ESA and NASA

Corona

- T = 2 x 106 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.



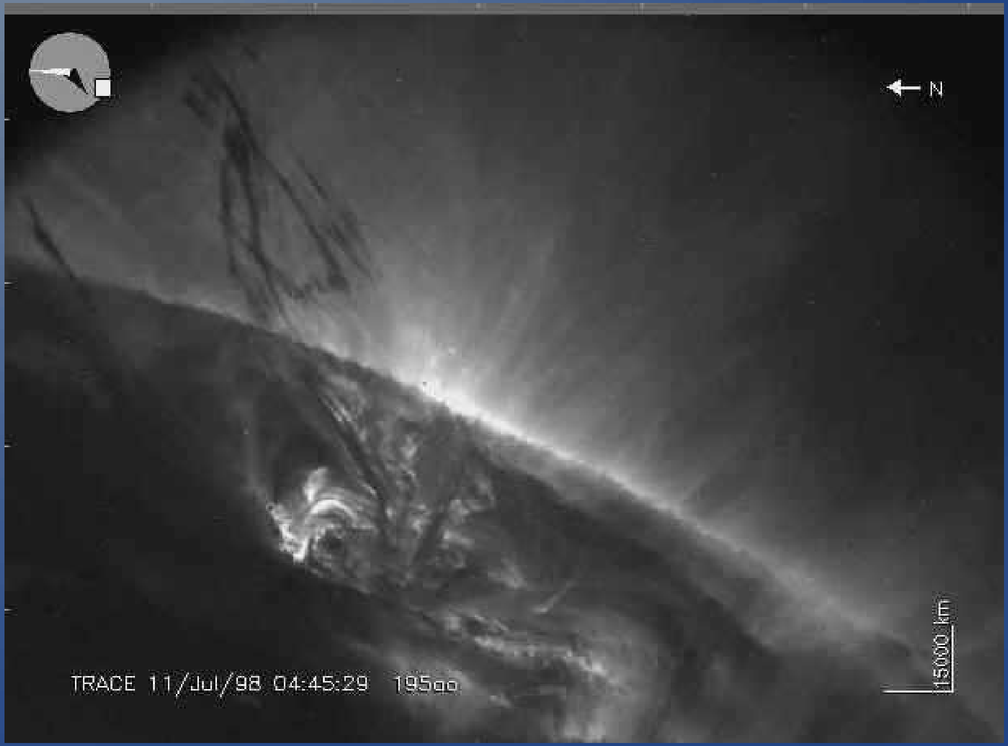
X-ray image (YOHKOH telescope)



Visible image

Coronal Features

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

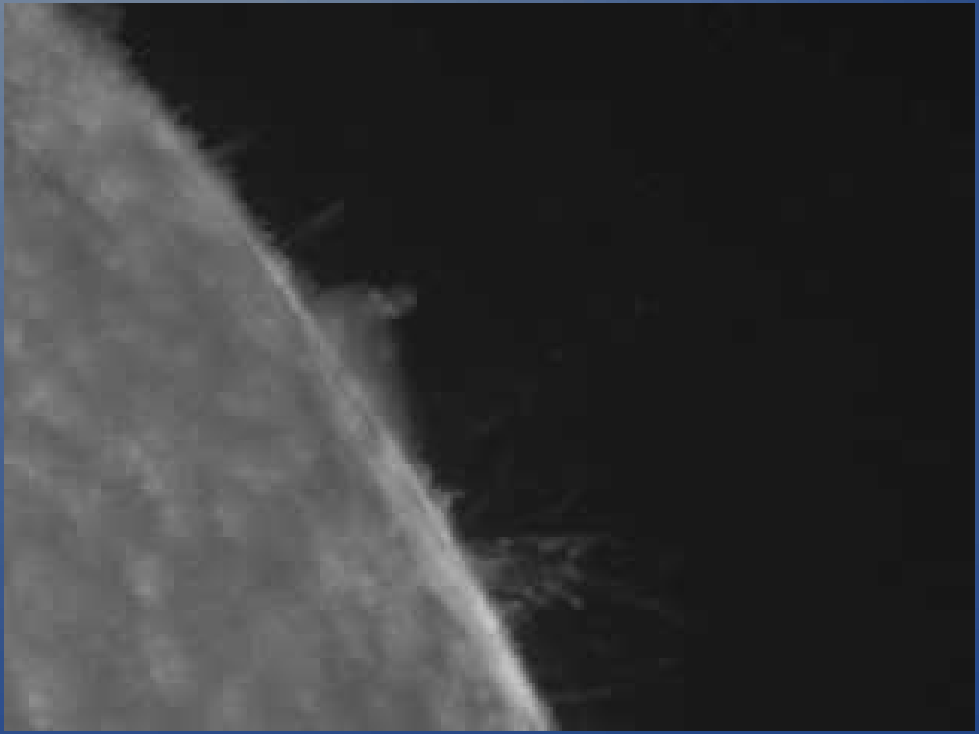


X-ray images from NASA's TRACE mission.

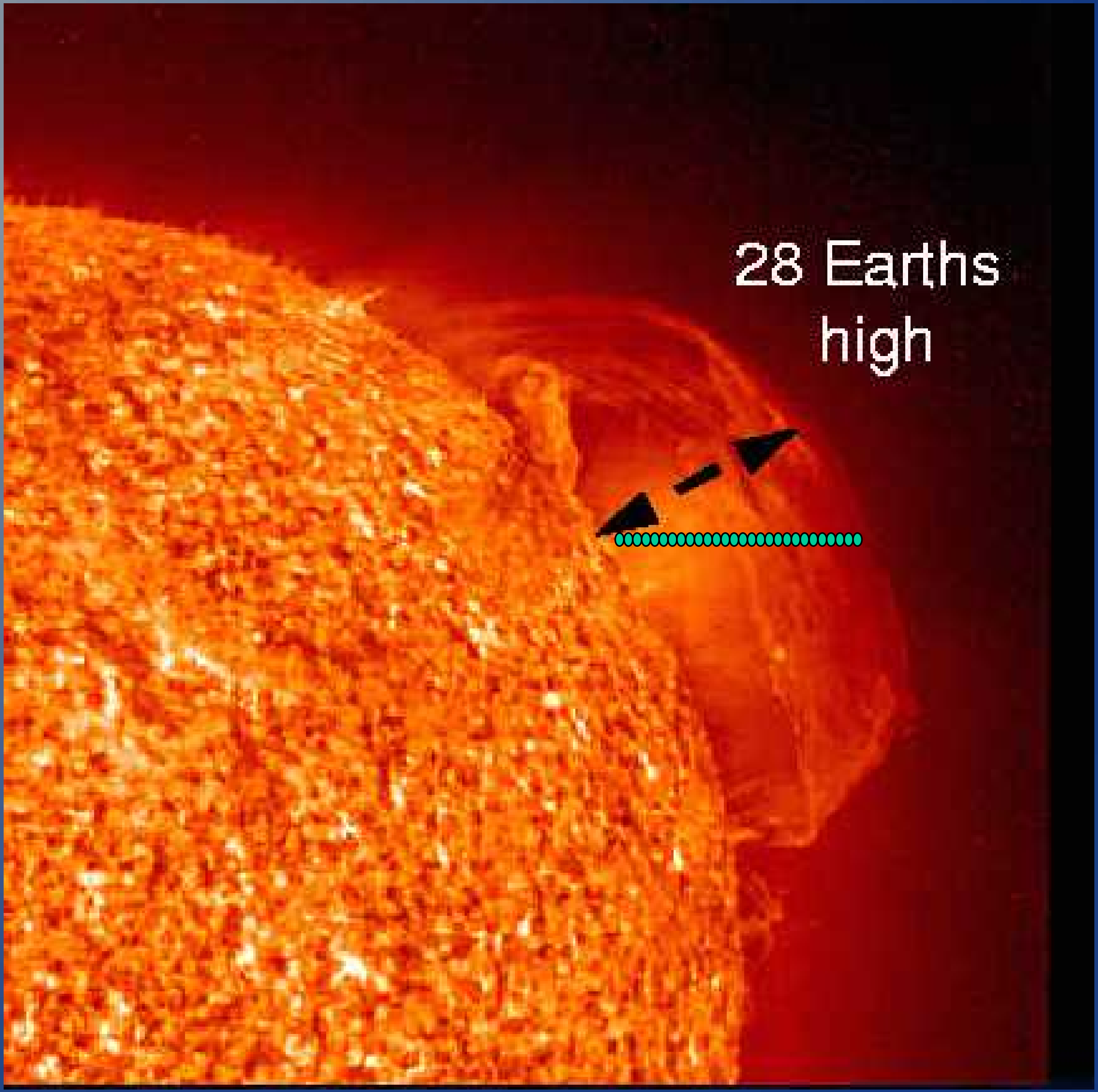
Movie. Click to launch.

Coronal Features

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

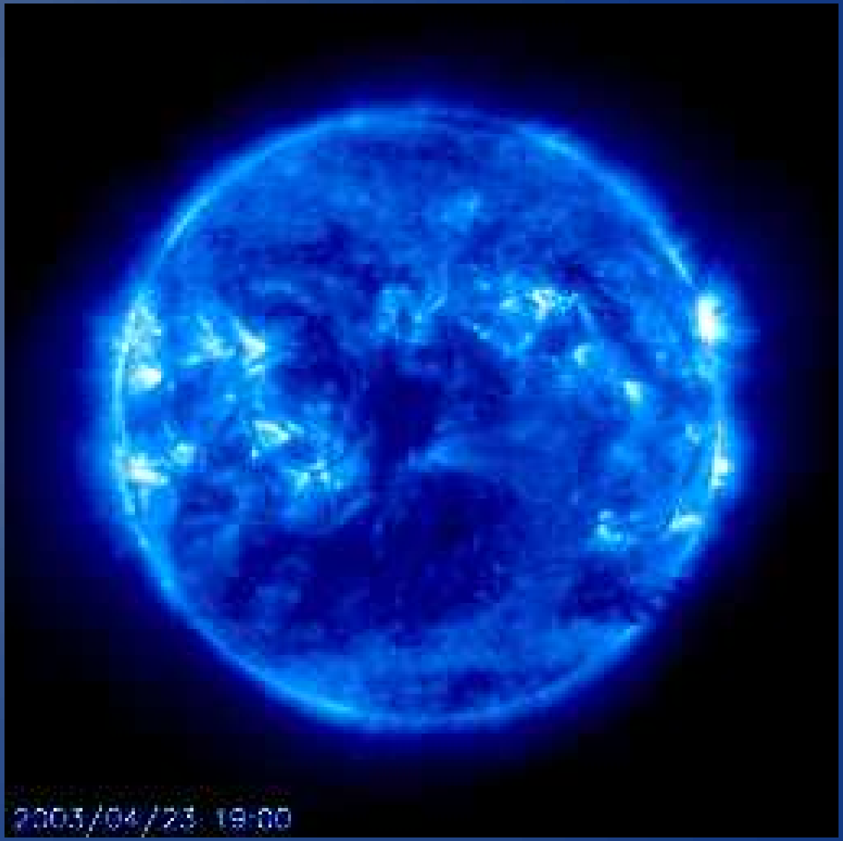


X-ray images from NASA's TRACE mission.


28 Earths
high

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 temperature starts to increase above the photosphere.

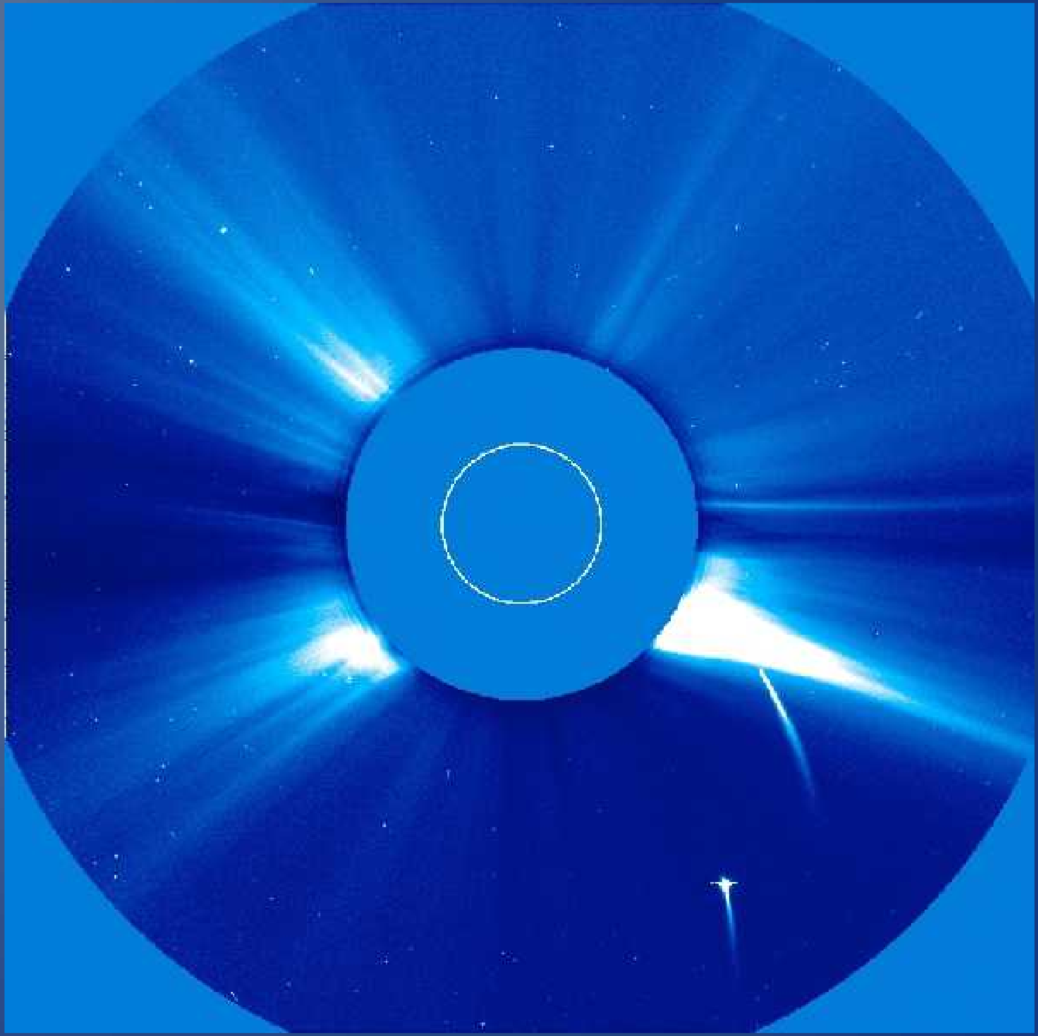


courtesy of SOHO/EIT consortium
SOHO is a project of ESA and NASA

The corona ejects some of its mass into space as the solar wind

Solar Wind

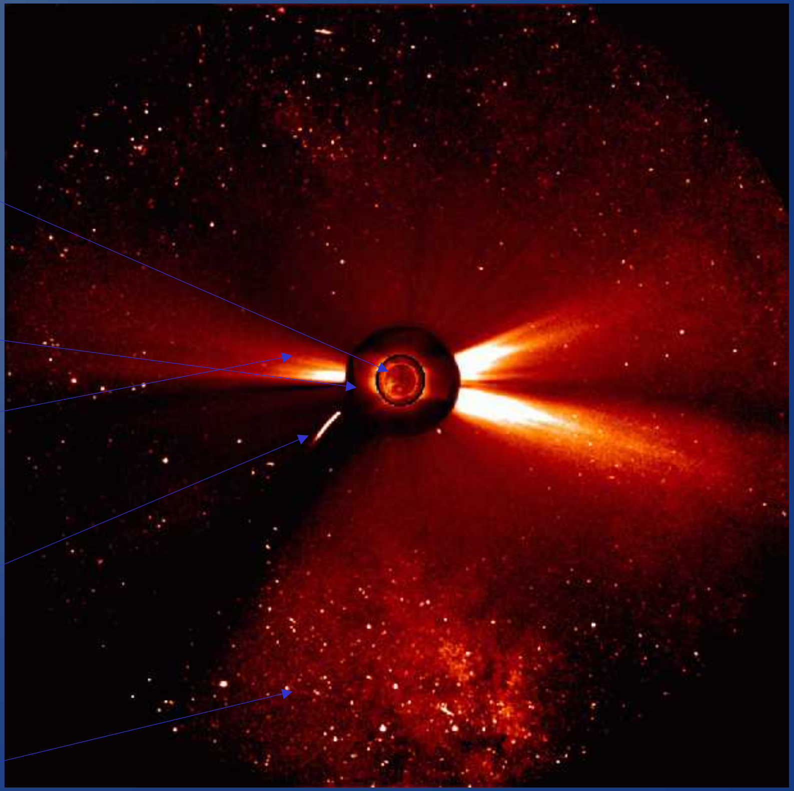
- When magnetic field lines break, they release the charged particles into space.
- This so-called **solar wind** escapes through the coronal holes.



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

Solar Wind

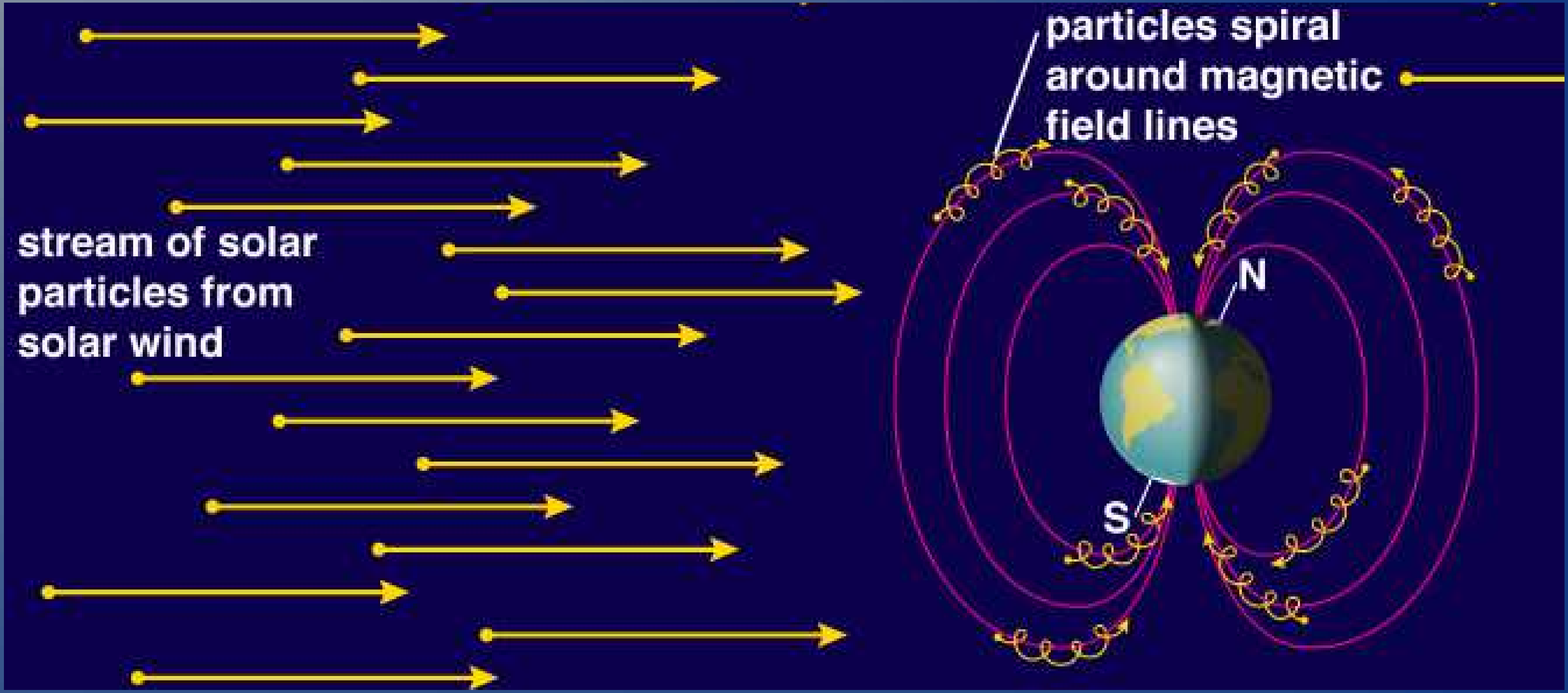
- The stream of electrons, protons, Helium nuclei and other ions which flow out from the Sun.
- It extends out beyond Pluto.



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

Solar Wind

electrons, protons, He nuclei expelled by flares



The Aurorae

the Northern & Southern Lights

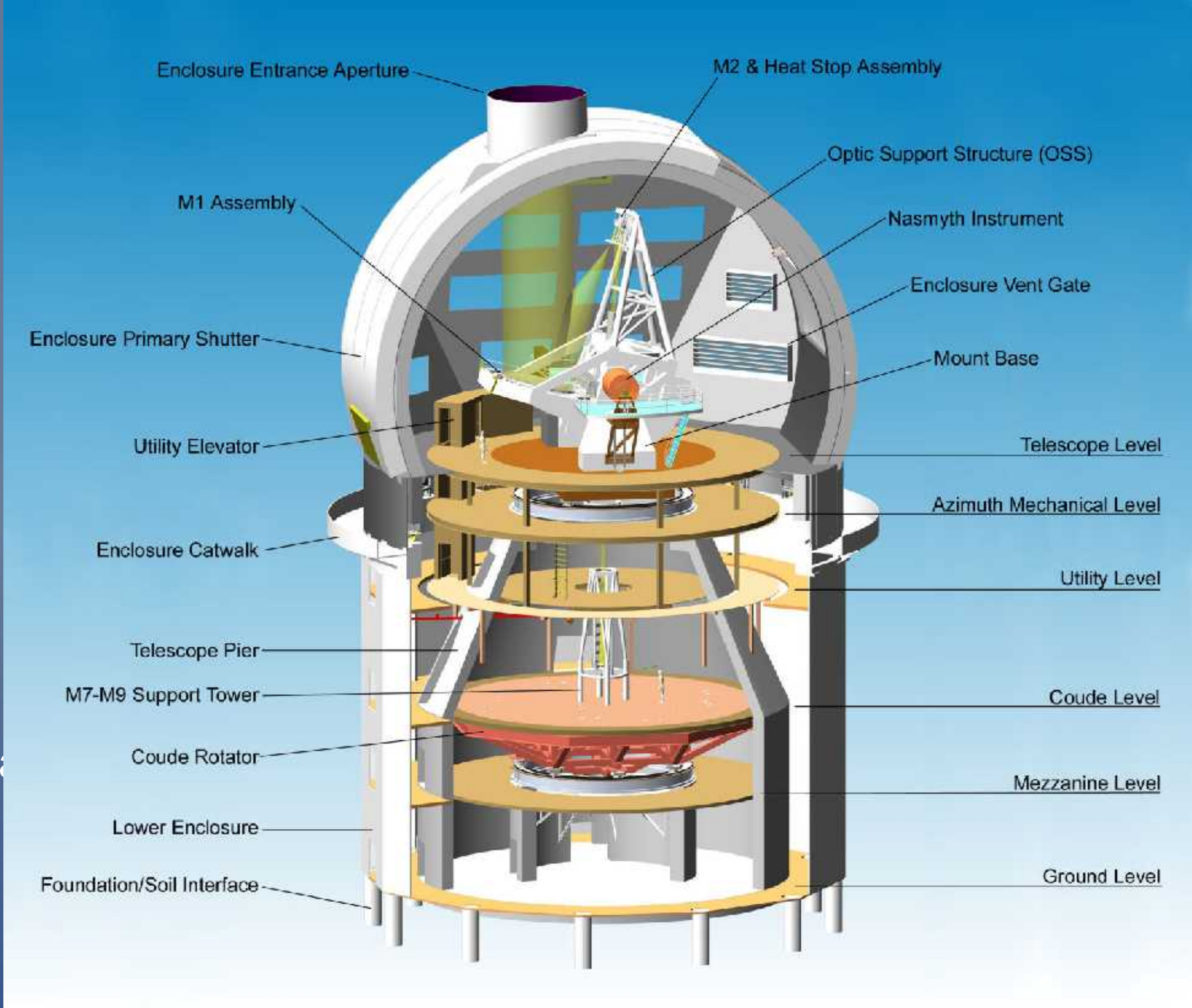
- A strong Solar wind can affect human technology by:
  - interfering with communications
  - knocking out power grids
  - damage electronics in space vechicles
- We are not yet sure of the effect which Solar activity has on Earth's climate.

Remember?
New Projects for the IfA:

- Pan STARRS
- Advanced Technology Solar Telescope

Advanced Technology Solar Telescope

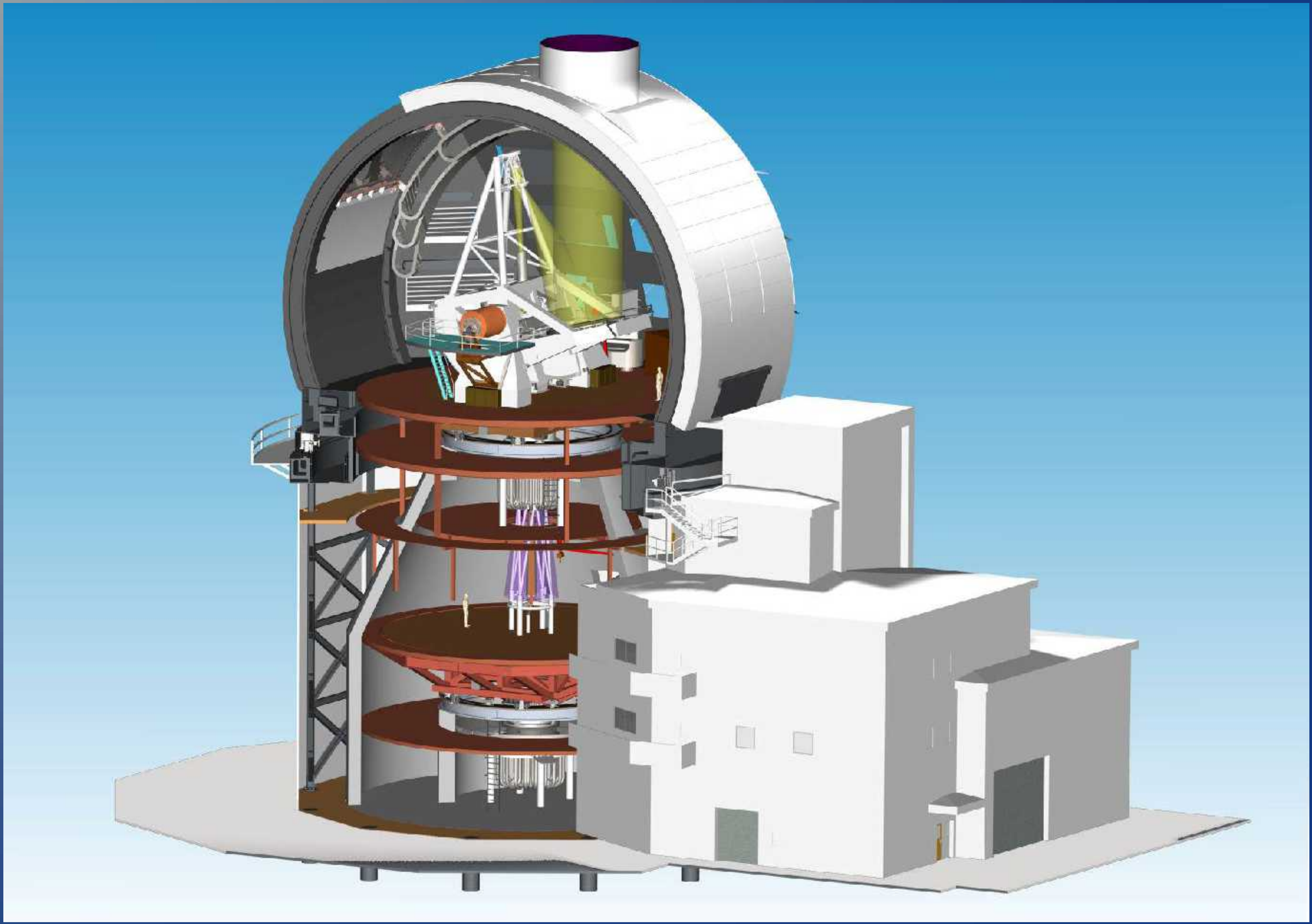
- **world's largest solar telescope** to study solar cycle and global warming
- **$ 100M project**, engineering study funded (NSF)
- prototype built on Haleakal

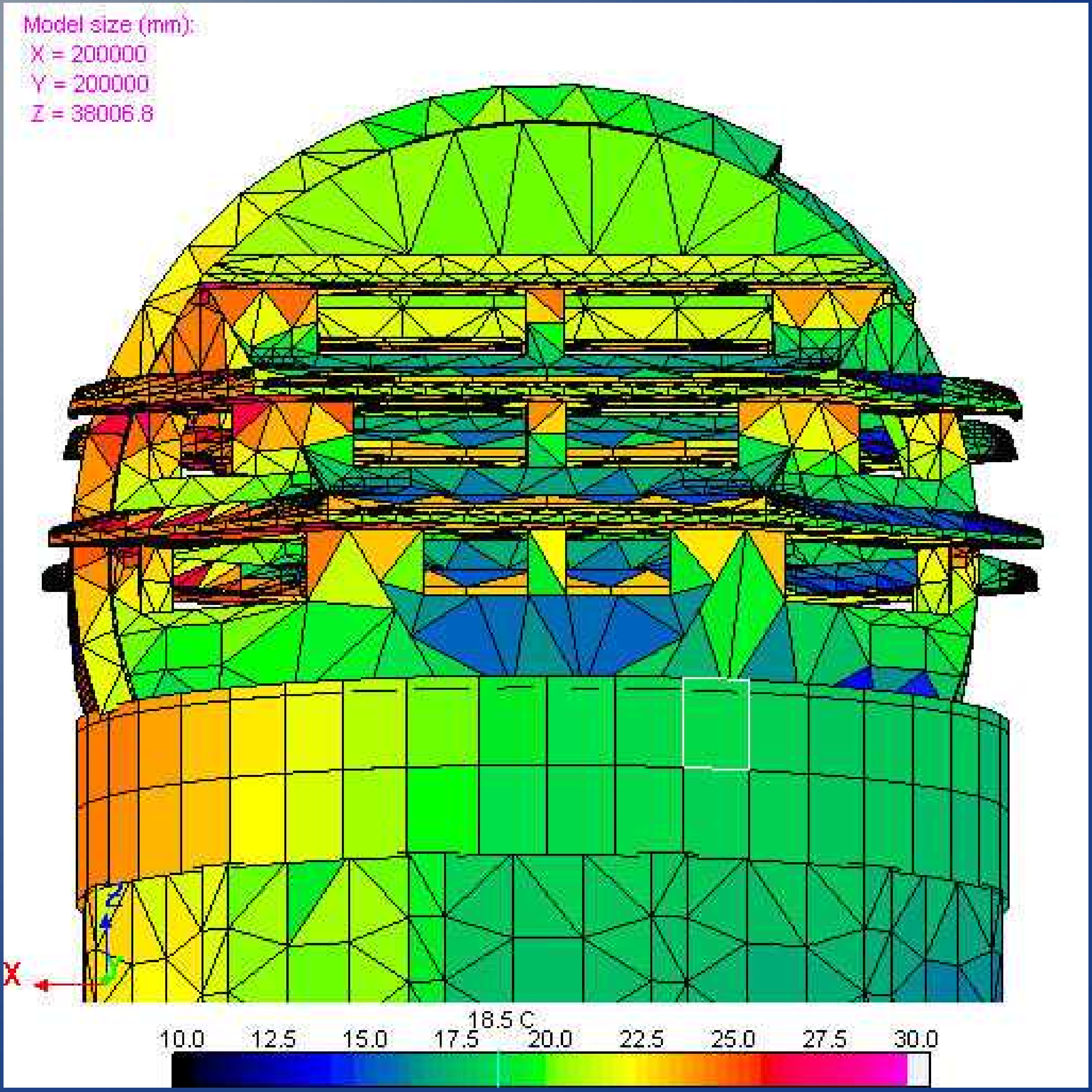


- **Haleakalä** has been selected as the prime site
- can also attract National Solar Observatories to Maui

Rendering of proposed ATST facility at the primary Mees site on Haleakalā, Maui, Hawaii by Tom Kekona, K. C. Environmental, Inc. Original aerial photo by Frank Rizzo.


FAA & DOE
A.F. MSSC
& GEODSS
A.F. AEOS
Utilities &
Neutron Mon.
FAA
Low
Site
Mees
Solar-C
Reber
Circle
Broadcast
Antennae
(private)
MAGNUM
PS-1
ATST at
Mees Site




Model size (mm):
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Z = 38006.8
Z
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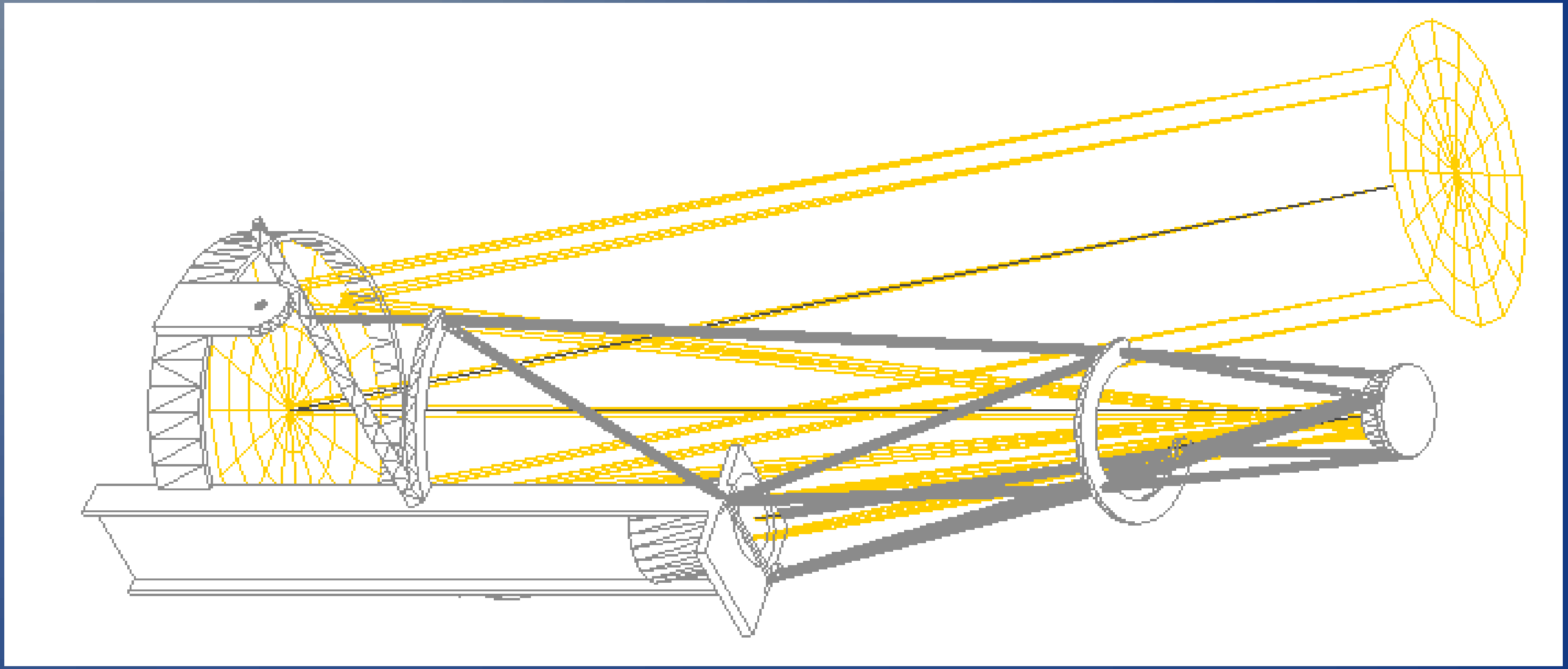
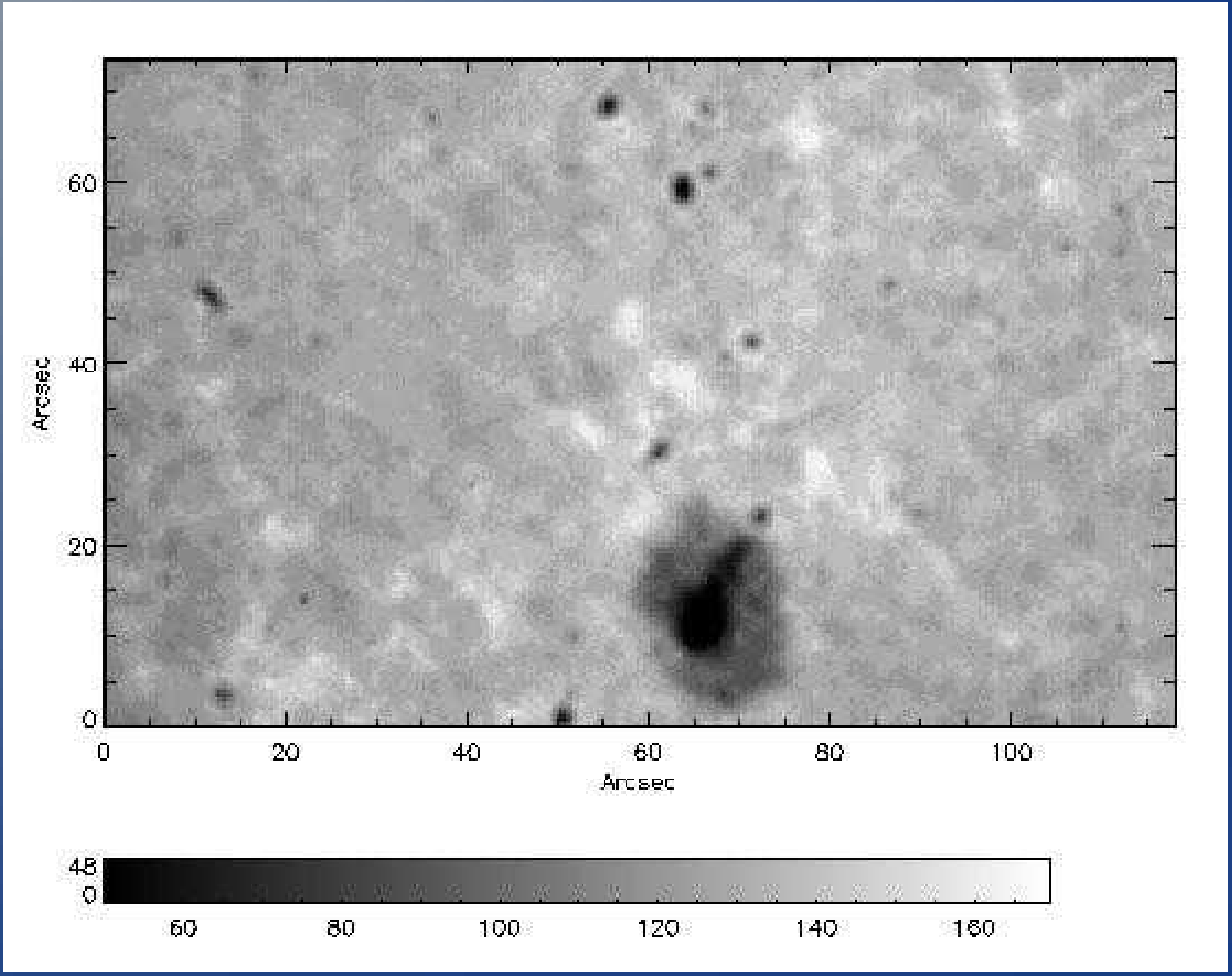
Solar - C Off Axis Telescope



First light image proves technology



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.
- 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 should you know?

- Which two energy sources can help a star maintain its internal thermal pressure?
- What is a possible solution to the solar neutrino problem?
- The light radiated from the Sun's surface reaches Earth in about 8 minutes, but the energy of that light was released by fusion in the solar core when?
- What is the temperature of the core of the Sun?
- Based on its surface temperature of 5,800 K, what color are most of the photons that leave the Sun's surface?
- Suppose you put two protons near each other, what will happen?
- How does the Sun generate energy today?
- How much mass does the Sun lose through nuclear fusion per second? (4 million kg)
- What processes are involved in the sunspot cycle?
- How are luminosity and flux or brightness related?

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.
- 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?

- 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.

What did you think?

- *What is the surface of the Sun like?*

The photosphere is composed of hot, churning gases. There is no solid or liquid region in the Sun.

- *Does the Sun rotate?*

The Sun's surface rotates differentially. The rate varies between once every 25 and once every 35 days.

What did you think?

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- *Does the Sun rotate?*

The Sun's surface rotates differentially. The rate varies between once every 25 and once every 35 days.

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.

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