The Sun

- The Sun is a huge ball of gas at the center of the solar system
  - 100 times Earth diameter, 300,000 earth mass
  - 1 million Earths would fit inside it!
  - Releases the equivalent of 100 billion atomic bombs every second!
- Exists thanks to a delicate balance of gravity and pressure

Looks “quiet in the visible”

- The immense mass of the Sun generates a huge gravitational force
  - Gravity pulls all of the Sun’s matter toward its center
  - This crushing force produces a high temperature and pressure on the interior of the Sun
- This balance of gravity and pressure will allow a star like the Sun to live for billions of years

Looks violent in UV and X-ray
Knowledge of interior based on models which fit observables:

- Mass
- Radius
- Luminosity
- Surface Temperature
- Image details: granules, spicules, corona, chromosphere

The photosphere

- The *photosphere* is the visible “surface” of our star
  - Not really a surface, as the Sun is gaseous throughout
  - Photosphere is only 500 km thick
  - Average temperature is 5780 K
• Most of the features we can see are located in the photosphere.
• Regions of rising gas that look like bubbles are called granules, and represent the transport of energy from deeper in the Sun to its atmosphere.
• Sunspots can be found in the photosphere.
  – Actually cooler than their surroundings!

• Just below the photosphere is the convection zone.
  – Energy is transported from deeper in the Sun by convection, in patterns similar to those found in a pot of boiling water (hot gas rises, dumps its energy into the photosphere, and then sinks).
• Energy in the convection zone comes from the radiative zone.
  – Energy from the core is transported outward by radiation.
  – Takes more than 100,000 years for a single photon to escape the Sun!
Regions of the Sun above the photosphere are called the Sun’s atmosphere.

Just above the photosphere lies the chromosphere.
- Usually invisible, but can be seen during eclipses.
- *Spicules*, found here, look like a prairie grass fire!

Above the chromosphere is the corona.
- Extremely high temperatures (more than 1 million K!)
- Rapidly expanding gas forms the solar wind.

The energy of a photon emitted by thermonuclear processes in the core of the Sun takes thousands or even millions of years to emerge from the surface because:

a) it is circling in the gravitational field of the Sun.

b) it loses energy due to convection, conduction, and radiation.

c) of the Sun's enormous radius.

d) it is absorbed and re-emitted countless times along the way.
• Stars like the Sun can be seen as having a kind of thermostat
  – Gravity pulls inward, pressure pushes outward.
  – If temperature begins to fall, pressure decreases and gravity pulls more mass toward the center
  – This inward-falling mass increases the temperature and pressure, restoring balance!

The Ideal Gas Law

\[
\text{Pressure} = \text{Constant} \times \text{Temperature} \times \text{Density}
\]
According to the Ideal Gas Law, if the temperature in the core of a star is made 4-times higher, which of the following can happen?

a) The pressure increases by 4 times and the density remains the same
b) The density increases by 4 times and the pressure remains the same
c) Its pressure and density both double.
d) The pressure increases by 4 times while density decreases by 4 times
e) Its pressure and density both decrease by 2.

How do we know all of this?

• Naturally, we’ve never seen the inside of the Sun
  – Computer models suggest the layered structure we’ve discussed
  – We can probe the interior using *helioseismology*, the study of sunquakes!
The Sun’s Energy

- The Sun’s energy comes from fusion – the merging of hydrogen nuclei into helium
- The reaction releases only a little bit of energy, but it happens a lot!
- A hydrogen nucleus has less mass than the four protons (hydrogen nuclei) that fuse
- This difference in mass is converted into energy:

\[ E = m\times c^2 \]

Temperature and Pressure Are the Key

- In the core of the Sun, the temperature exceeds 15 million K, and the pressure is very high
- High temperatures imply that the nuclei in the core are moving very fast, and the high pressure is pushing them together
- The high speeds of the nuclei allow them to collide and fuse via the proton-proton chain
The Proton-Proton Chain

Neutrinos

• One product (aside from energy) of the proton-proton chain is a neutrino
  – Very low mass, very high energy particle
  – Passes through matter very easily, and so is hard to detect
  – Neutrino measurements on Earth confirm our models of fusion in the Sun’s core
Neutrinos

- One product (aside from energy) of the proton-proton chain is a neutrino
  - Very low mass, very high energy particle
  - Passes through matter very easily, and so is hard to detect
  - Neutrino measurements on Earth confirm our models of fusion in the Sun’s core

Sunspots

- Sunspots are highly localized cool regions in the photosphere of the Sun
  - Discovered by Galileo
  - Can be many times larger than the Earth!
  - They contain intense magnetic fields, as evidenced by the Zeeman effect
Sunspots appear dark because they are
a) holes in the photosphere through which you can see deeply into the stellar interior.
   b) a bit cooler and thus dimmer than the rest of the photosphere.
   c) large opaque structures that block light from the glowing solar surface.
   d) causing retinal damage.

Solar Flares

• Solar flares are huge eruptions of hot gas and radiation in the photosphere
• Can damage satellites, spacecraft, and humans in space
• The study of coronal mass ejections and solar flares is called “space weather”
A Coronal Mass Ejection

When CME material reaches the Earth, it interacts with the Earth’s magnetic field and collides with ionospheric particles.

The collision excites ionospheric oxygen, which causes it to emit a photon.

We see these emitted photons as the aurora, or Northern Lights.

The Aurora
The Solar Cycle

- The number of sunspots seen increases and decreases periodically.
- Every 11 years or so, the sunspot number peaks. This is called Solar Maximum.
- Around 5.5 years after Solar Maximum, the sunspot number is at its lowest level. This is called Solar Minimum.
- Solar activity (CMEs, flares, etc.) peaks with the sunspot number.

Differential Rotation

- Different parts of the sun rotate at different speeds:
  - Equator rotates faster than the poles.
  - Solar magnetic fields get twisted as time goes on.
Which of the following do NOT follow an 11 year cycle?
   a) The number of sunspots on the Sun.
   b) The typical latitude of sunspots on the Sun.
   c) The rate of solar flares.
   d) Incidence of strong aurora on the Earth.
   e) None of the above.