Chapter 10
Our Star

X-ray visible
**Radius:**
6.9 \times 10^8 \text{ m}
(109 times Earth)

**Mass:**
2 \times 10^{30} \text{ kg}
(300,000 Earths)

**Luminosity:**
3.8 \times 10^{26} \text{ watts}
(more than our entire world uses in 1 year!)
Why does the Sun shine?
Is it on FIRE?
Is it on FIRE?

\[
\frac{\text{Chemical Energy Content (J)}}{\text{Luminosity (J/s = W)}} \approx 10,000 \text{ years}
\]
Is it on FIRE? ... NO

Chemical Energy Content

\[ \text{Luminosity} \approx 10,000 \text{ years} \]
Is it CONTRACTING?
Is it CONTRACTING?

\[
\frac{\text{Gravitational Potential Energy}}{\text{Luminosity}} \approx 25 \text{ million years}
\]
Is it CONTRACTING? ... NO

Gravitational Potential Energy

Luminosity

~ 25 million years
It is powered by NUCLEAR ENERGY!

Nuclear Potential Energy (core)  ~  10 billion years
_______________________________
Luminosity
It is powered by NUCLEAR ENERGY!

- Nuclear reactions generate the Sun’s heat
- But they require very high temperatures to begin with
- Where do those temperatures come from?
- They come from GRAVITY!

\[ E = mc^2 \]

—Einstein, 1905
• The tremendous weight of the Sun’s upper layers compresses interior.
• The intense compression generates temperatures $>10^7$ K in the innermost core.
• And that’s where the nuclear reactions are.
The compression inside the Sun generates temperatures that allow fusion. The fusion reactions in turn generate outward pressure that balances the inward crush of gravity. The Sun is in a balance between outward pressure from fusion and inward pressure from gravity. This is called gravitational equilibrium.
The Sun’s Structure
Solar wind:
A flow of charged particles from the surface of the Sun.
Core:
Energy generated by nuclear fusion
Temps to 15 million K

Radiation zone:
Energy transported upward by photons
Temps to 10 million K

Convection zone:
Energy transported upward by rising hot gas
Temps to 1 million K

Photosphere:
Visible surface of Sun
Temp ~ 6,000 K

Chromosphere:
Middle layer of solar atmosphere
Temp ~ 10⁴–10⁵ K

Corona:
Outermost layer of solar atmosphere
Temp ~ 1 million K
How does the Sun produce energy?
Two kinds of nuclear reactions

Big nucleus splits into smaller pieces

(Nuclear power plants)

Small nuclei stick together to make a bigger one

(Sun, stars)
• The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.
• The hydrogen nuclei (protons) have to touch for this to happen
• For them to touch requires temperatures > 10,000,000 K
• Why does it have to be so hot?
• Why would that require high temperatures?

\[ KE_{avg} = \frac{3}{2} kT \]
• This is the way the Sun produces its energy
• But this is a summary reaction
• The actual reaction—the proton-proton chain—is more complex
• This is the complete reaction…the proton–proton chain
• It’s interesting how long each of these steps takes…
IN
4 protons

OUT
\(^4\)He nucleus

6 gamma rays

not two as shown here

Anybody know why?

2 positrons

annihilate with two e\(^-\)
to produce two \(\gamma\) rays

2 neutrinos

The total mass is 0.7% lower

The Sun’s energy comes from this…

\[ E = mc^2 \]

• This reaction is very sensitive to temperature
• Which makes the “solar thermostat” possible…
Decline in core temperature causes fusion rate to drop, so core contracts and heats up

Rise in core temperature causes fusion rate to rise, so core expands and cools down
How does the energy from fusion get out of the Sun?
• Energy passes through the radiation zone in the form of randomly bouncing photons.
• This can take up to a million years…
• Convection (rising hot plasma) takes energy to the surface in the convection zone
• This takes about a week
This is a close-up of the photosphere of the Sun
The brighter areas are where hot plasma reaches the photosphere.
The darker areas are where cool plasma sinks back down
This is called “granulation” because of the way it looks
Granulation is not static, and the “granules” are not small
Motion sped up ~600X       Total actual elapsed time = 35 min

Average size of a convection cell ~1300 km (800 miles)

Speed of gas motion 1-2 km/s (2000-4000 mph)
How do we know what goes on inside the Sun?
This is how

- make mathematical and computational models
- use them to predict things about the Sun
  - the way the Sun vibrates
    - test internal structure and composition
  - the number of neutrinos the Sun produces
    - test nuclear reaction mechanism
- observe solar vibrations
- observe solar neutrinos
- compare observations to predictions

Does this process sound familiar?

THE SCIENTIFIC METHOD
• Patterns of vibration on the surface tell us about what the Sun is like inside.

• Models of the interior of the Sun are adjusted until the vibrations of the model match the observed vibrations of the Sun.
• Here is a movie made from observations of the vibrating surface of the Sun

From http://solarscience.msfc.nasa.gov/Helioseismology.shtml
• And here is a movie of one vibration “mode” made from a *model of the Sun*

*From* [http://solarscience.msfc.nasa.gov/Helioseismology.shtml](http://solarscience.msfc.nasa.gov/Helioseismology.shtml)
A single vibration mode can be considered to combine two modes.

From http://solarscience.msfc.nasa.gov/Helioseismology.shtml
• Surface vibrations can tell us if we understand the Sun’s internal structure, composition, and conditions

From http://solarscience.msfc.nasa.gov/Helioseismology.shtml

• But to find out if we understand how it generates energy, we need to look here on Earth – or really inside the Earth – for *neutrinos*
This is how we think the Sun generates its energy. But how can we test it? The proton-proton chain produces a certain number and type of neutrino. Unlike gamma rays, neutrinos don’t interact very much with the Sun. In fact, they fly directly through any normal matter. There are trillions of them flying through each of us right now. And they come straight out of the Sun to Earth. So looking at them is nearly as good as looking right at the nuclear reactions going on in the core.
Solar neutrino problem:

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Solar neutrino problem:
- Early searches for solar neutrinos found only $\sim 1/3$ of the predicted number.
- It took 20 years, until scientists understood neutrino behavior better, to figure out why.
- On the way to Earth from the Sun, the neutrinos changed form from the type produced in the proton-proton chain ($\nu_e$) to the other two types ($\nu_\mu$ and $\nu_\tau$).
- When this is taken into account, the observed number matches predictions.
The Sun–Earth Connection

- What causes solar activity?
- How does solar activity affect Earth?
- How does solar activity vary with time?
What causes solar activity?
Types of Solar Activity

• Sunspots
• Solar flares
• Solar prominences
• Coronal mass ejections
• All related to magnetic fields.
Sunspots...

- Cooler than other parts of the Sun’s surface (4,000 K)
- Strong magnetic fields
- How do we know?
- The Zeeman Effect
We can detect magnetic fields in sunspots by observing the splitting of spectral lines.
The Sun’s magnetic field is essentially the same as an electromagnet’s field...and a planet’s magnetic field. Charged particles circulate as an electric current in looped paths. This generates the magnetic field. Convection of the plasma beneath the surface of the Sun causes its field. Sunspots occur where field lines poke out of the Sun’s surface...we’ll see why in a bit...

And this keeps the sunspot cooler than the surrounding plasma. Here’s how...
• Charged particles spiral along magnetic field lines
• Field lines “fence out” hot plasma
• Allows sunspots to exist for long periods...
• Loops of bright gas often connect sunspot pairs
• The gas is following magnetic field lines
• Magnetic activity causes solar flares that send bursts of X-rays and charged particles into space.

• Flares happen when magnetic field lines reorganize themselves, snapping together something like rubber bands.

• The energy released heats the chromosphere and corona and generates high levels of radiation and particles.
• Magnetic activity also causes solar prominences that erupt high above the Sun’s surface.

• A big one occurred on April 13th 2010...
The Sun was quite active in early July 2012 as well.
This is a UV image of part of the surface then.
Even more impressive is the movie available at this NASA web page:
http://svs.gsfc.nasa.gov/vis/a010000/a011000/a011044/index.html
• The corona appears brightest in X-ray photos in places where magnetic fields stir and trap hot gas.
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• This typically occurs above sunspots

• This is believed to contribute to the surprisingly hot temperature in the corona
• Coronal mass ejections send bursts of energetic charged particles – really whole chunks of the Sun – out through the solar system.

• A CME accompanied the April 13\textsuperscript{th} 2010 prominence
• Charged particles streaming from the Sun, especially during a CME, can disrupt electrical power grids and disable communications satellites.
• And all of this activity is tied to the Sun’s magnetic field
• The Sun’s magnetic field varies in a more or less regular way
• The most obvious manifestation of the variation is the number of sunspots
• The number of sunspots rises and falls in 11-year cycles.
• One way of tracking sunspot variation is to measure the percentage of the Sun’s surface covered by sunspots
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• One way of tracking sunspot variation is to measure the percentage of the Sun’s surface covered by sunspots
• Another way is to look at where the sunspots are
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The sunspot cycle has to do with the winding and twisting of the Sun’s magnetic field. Think of the Sun’s magnetic field as lines of bar magnets end-to-end. The Sun’s equator rotates faster than the poles. This eventually breaks apart magnetic linkages (like breaking apart the lines of bar magnets). Sunspots form where the broken magnetic fields poke out.
The global magnetic field reorganizes itself at each solar minimum, but the polarity is opposite what it was at the previous minimum. There are 11 years between maxima, but the full cycle lasts 22 years.