Chapter 10
Our Star

X-ray visible

Radius: 6.9 × 10^8 m
(109 times Earth)

Mass: 2 × 10^30 kg
(300,000 Earths)

Luminosity: 3.8 × 10^26 watts
(more than our entire world uses in 1 year!)

Why does the Sun shine?
Is it on FIRE?  … NO

Chemical Energy Content (J)   
Luminosity (J/s = W)           ~ 10,000 years
Is it CONTRACTING? 

Luminosity 
Gravitational Potential Energy 

... NO 

Gravitational Potential Energy 
Luminosity 

~ 25 million years
It is powered by NUCLEAR ENERGY!

Nuclear Potential Energy (core) \[ \frac{E}{Luminosity} \approx 10 \text{ billion years} \]

• 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!

• The tremendous weight of the Sun’s upper layers compresses interior
• The intense compression generates temperatures \( > 10^7 \text{ K} \) 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**

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**Gravitational Equilibrium**

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**The Sun’s Structure**

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**Solar wind:** A flow of charged particles from the surface of the Sun
How does the Sun produce energy?

Two kinds of nuclear reactions

- **Fission**
  - Big nucleus splits into smaller pieces
  - (Nuclear power plants)

- **Fusion**
  - 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?

\[ KE_{\text{avg}} = \frac{3}{2} kT \]

• 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

Anybody know why?
2 positrons annihilate with two e⁻ to produce two γ rays
2 neutrinos

The total mass is 0.7% lower
The Sun’s energy comes from this...

E = mc²

This reaction is very sensitive to temperature
That sensitivity, together with gravitational equilibrium, makes the “solar thermostat” possible...

Solar Thermostat

- Core temperature drop -> fusion rate drop
- Gravity crunch exceeds pressure push
- Core compression -> temperature rise
- Original conditions restored

- Core temperature rise -> fusion rate rise
- Pressure push exceeds gravity crunch
- Core expands -> temperature drops
- Original conditions restored
How does the energy from fusion get out of the Sun?

- Gamma ray photons from the core bounce randomly through the radiation zone
  - This can take up to a million years…

- Plasma convection takes energy to the surface of the convection zone
  - This takes about a week
  - The surface of the convection zone is the visible surface of the Sun—the photosphere
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)
We've talked about the Sun's structure
We've talked about how it generates energy
But how do we know we're right?

• make mathematical and computational models of the Sun
• use them to predict things about the Sun, e.g.:
  – predict the way the Sun vibrates based on hypotheses about internal structure and composition
  – predict the number of neutrinos the Sun produces based on hypotheses about the nuclear reaction mechanism
• observe solar vibrations
• observe solar neutrinos
• compare observations to predictions

Does this process sound familiar?
THE SCIENTIFIC METHOD

This is how

• 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.

This is how we think the Sun generates its energy:
- The proton-proton chain produces a certain number and type of neutrino.
- Unlike gamma rays, neutrinos don't interact very much with the Sun.
- 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:
- Early searches for solar neutrinos found only ~1/3 of the predicted number.

In fact, they fly directly through any normal matter:
- There are trillions of them flying through each of us right now.

Picture of solar neutrino detector.
Solar neutrino problem:

- Early searches for solar neutrinos found only ~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

Types of Solar Activity

- Sunspots
- Solar flares
- Solar prominences
- Coronal mass ejections
- All related to magnetic fields
- We’re going to focus on sunspots

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...

How do magnetic fields make sunspots "cool"?

- 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

All of solar activity—sunspots, flares, etc.—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

Another way is to look at where the sunspots are
• 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

min  max  min  max  min

• There are 11 years between maxima, but the full cycle lasts 22 years

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A Hertzsprung-Russell diagram plots luminosity versus surface temperature or spectral type. Remarkably, that tells you everything you need to know about a star you are interested in to have access to lots of information about it. Once the star's on the H-R diagram, you can find out if it's a giant, main-sequence star, or what kind it is. You'll have estimates of its mass, radius, and main-sequence lifetime (if it's a main-sequence star, which most stars are). How long stars stay on the main sequence depends on their mass, which varies greatly from star to star. More massive stars don't stay as long on the main sequence. After the main sequence, the "core thermostat" no longer works.

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On the main sequence, the "core thermostat" works:
• While a star is on the main sequence, it has a core thermostat, like our Sun's solar thermostat.
• It keeps the rate of H->He fusion constant.
• And that fusion supports the core and the star through gravitational equilibrium.
• When hydrogen is used up, H->He fusion turns off.
• The core is now all helium, no hydrogen.
• The star is dying.
After the Main Sequence - Broken Thermostat

- With no fusion energy, the He core contracts (is compressed) and heats.
- The hot core acts like a stove burner, causing H to fuse to He in a shell around the core.
- This produces even more outward pressure than on the main sequence, and the star swells up into a "red giant".
- The burning shell doesn't restore the "core thermostat", because it is outside the core.
- Meanwhile the hydrogen-burning shell continues to deposit the "ash" on the core, and it continues to heat up.
- Eventually it gets hot enough (100 million K) for He to fuse to carbon.
- It becomes a "helium-burning star..."

Double-Shell Burning

- After core helium fusion stops, the carbon core collapses (is compressed) and heats.
- Meanwhile hydrogen continues to burn in a shell around the carbon core, depositing a shell of helium on the core.
- The shell of helium begins fusing to carbon while the hydrogen shell above it fuses to helium.
- The star becomes a red giant again, this time called a "double-shell burning star".
- This double-shell burning stage is unsteady, and the fusion rate periodically spikes upward in a series of thermal pulses.
- With each pulse, carbon gets dredged up from the core and transported into the overlying "envelope".
- Soon that carbon will enrich the interstellar medium...
- The carbon continues to shrink and get hotter.
- But its atoms "touch" before it gets hot enough (600 million K) to fuse carbon.
Planetary Nebulae and White Dwarfs

- Double-shell burning ends with a pulse that ejects the gas envelope into space as a planetary nebula.

Life stages of a low-mass star like the Sun

- Double-shell burning ends with a pulse that ejects the gas envelope into space as a planetary nebula
- The core left behind becomes a white dwarf
- White dwarfs are inert balls of carbon and oxygen (from fusion of helium and carbon)
- They might also have a little residual H/He atmosphere
• Double-shell burning ends with a pulse that ejects the gas envelope into space as a planetary nebula
• The core left behind becomes a white dwarf
• White dwarfs are inert balls of carbon and oxygen (from fusion of helium and carbon)
• They might also have a little residual H/He atmosphere
• They are about the size of Earth

For more information about the diamond star, see http://www.cfa.harvard.edu/news/archive/pr0407.html

• The planetary nebulae surrounding white dwarfs come in all shapes and sizes
The planetary nebulae surrounding white dwarfs come in all shapes and sizes.
Life Stages of High-Mass Stars

- Main-sequence life of high-mass stars is similar to low-mass stars:
  - Hydrogen core fusion (main sequence), but faster

- Early stages after main sequence are similar for high-mass stars and low-mass stars:
  - Hydrogen shell burning (as a supergiant)
  - Helium core fusion (as a supergiant)
  - But high-mass stars can go beyond that and do “advanced nuclear burning”

CNO Cycle

- High-mass main-sequence stars fuse H to He at much higher rates than low-mass stars
- This is partly because their higher mass means higher core temperatures
- But it’s also because they use carbon, nitrogen, and oxygen as catalysts.
- The “CNO cycle” is shown at left
Advanced Nuclear Burning

- Advanced nuclear burning proceeds in a series of nested shells.
- It’s during this process—and afterwards—that stars synthesize most of the chemical elements.
- If the star is massive enough (> ~8M_\odot), T_\text{core} is high enough to make very large nuclei fuse.
- In these stars, a variety of different fusion reactions in the nested shells can make elements all the way up to iron.

- But iron is a dead end for fusion because nuclear reactions involving iron do not release energy.
- This is because iron has the lowest energy per nuclear particle of all elements.
- Elements smaller than iron can fuse with a release of energy.
- Elements larger than iron can fission with a release of energy.
- But iron cannot fuse to anything larger, or fission to anything smaller.
- So iron cannot generate any energy to support the core.
- And when iron appears, the star’s death is imminent.

- Advanced nuclear burning beyond that possible for a low mass star proceeds in a series of nested shells until iron appears.
- Once iron appears, the dying star’s fate is sealed.
- The iron can’t fuse, so the core collapses in a matter of milliseconds.
Supernova Explosion

- Why does this cause a supernova?
- The collapse heats the core to the point that the iron nuclei dissociate into protons and neutrons.
- The protons then combine with free electrons to produce more neutrons and neutrinos.
- With the loss of the electrons, electron degeneracy pressure disappears.
- The core collapses to a ball of neutrons, supported by neutron degeneracy pressure.

Supernova Remnant

- The energy released by the collapse of the core, the "bounce" when neutron degeneracy pressure kicks in, and the massive production of neutrinos drives outer layers into space.
- It also drives synthesis of chemical elements up to uranium.
- Left behind is either a neutron star or, if the core is massive enough to "break" the neutron degeneracy pressure, a black hole.
- The outer envelope of the star moves out into space, forming a nebula.
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054.

A star’s mass determines its entire life story because it determines its core temperature.
- High-mass stars have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
- Low-mass stars have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs.