Technology and Astronomy

Astronomical discoveries are often the result of technical innovations.
Two examples:
• CCD – charge coupled devices
• Laser guide star

Charge Coupling Device (CCD)

These are the devices which convert light into digital images
You probably own one….

• Last years Nobel prize in Physics went to the inventors of these devices.

Focusing Light

Digital cameras detect light with charge-coupled devices (CCDs)
• A camera focuses light like an eye and captures the image with a detector
• The CCD detectors in digital cameras are similar to those used in modern telescopes
Charge Couple Device in Astronomy

A 1.4 billion pixel chip for Astronomy:

Why does it take so long for your camera to read out an image?

CCD converts photons (light) into electrons. Then it measures the number of electrons.

http://astro.unl.edu/classaction/animations/telescopes/buckets.html

Adaptive Optics

Star viewed through turbulent atmosphere

Same star corrected with adaptive optics.

By rapidly changing the shape of a mirror in the telescopes light path, the variations from turbulence can be corrected.

How does adaptive optics help? (cartoon approximation)

Measure details of blurring from “guide star” near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed

http://www.ucolick.org/~max/289C/
Laser Guide Star

- If there isn’t a sufficiently bright object near your object of interest, you can create one with a laser.

Telle and Denman, AFRL
Factoid

- The laser was “invented” by Astronomer and Physicist Charles Townes
- Built a device called the MASER
  - Microwaves amplified by stimulated emission of radiation (we’ll talk about these later)
- Did the basic theoretical work on laser
  - Light amplified by stimulated emission of radiation
- One Nobel Prize in physics in 1964
- Received patent for laser

Today: The Sun and the Stars

- What is the structure of a star?
- How do stars produce energy?
- How does the energy travel from the center of the star to the surface?
- What is a solar wind and a solar flare?

The Sizes of the Terrestrial Planets

- Earth: 6370 km Radius
- Venus: 0.95 Earth’s Radius
- Mars: 0.53 Earths
- Mercury: 0.39 Earths
- Pluto: 0.19 Earths
- Moon (not shown): 0.27 Earths

The Sizes of the Giant Planets

- Jupiter: 11.2 Earth’s
- Saturn: 9.4 Earth’s
- Uranus: 4.0 Earth’s
- Neptune: 3.8 Earth’s
Where does the Sun’s Energy Come from?
Remember, the solar system is 4.6 billion years old!!

- Chemical Energy Content
  - Luminosity
  ~ 10,000 years

- Gravitational Potential Energy
  - Luminosity
  ~ 25 million years

- Nuclear Potential Energy (core)
  - Luminosity
  ~ 10 billion years

Stars are made of gas.
The density, temperature and pressure of the gas increases as we go from the surface to the core of a star.

Weight of upper layers compresses lower layers.

Gravitational contraction:
Without nuclear fusion:
As the sun radiated energy it would slowly contract so that gravitational potential energy would balance the lost of energy.

This is how the Sun generated energy early in its life (next week's lecture).
**Gravitational equilibrium:**

The Sun is not contracting.

Energy produced by nuclear fusion balances energy radiated into space.

Energy heats gas, maintaining pressure. The sun is in equilibrium.

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**What is the Sun’s structure?**

**Radius:**

6.9 x 10^8 m  
(109 times Earth)

**Mass:**

2 x 10^30 kg  
(300,000 Earths)

**Luminosity:**

3.8 x 10^26 watts

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**Solar wind:**

A flow of charged particles from the surface of the Sun.
**Corona:**
Outermost layer of solar atmosphere
~1 million K

**Chromosphere:**
Middle layer of solar atmosphere
~ $10^4 - 10^5$ K

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

**Convection Zone:**
Energy transported upward by rising hot gas
Radiation Zone:
Energy transported upward by photons

Core:
Energy generated by nuclear fusion
~ 15 million K

How is energy produced in the Sun?

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

**Fusion**
Small nuclei stick together to make a bigger one
(Sun, stars)

High temperature enables nuclear fusion to happen in the core

Sun releases energy by fusing four hydrogen nuclei into one helium nucleus
**Proton-proton chain** is how hydrogen fuses into helium in the Sun.

### Hydrogen Fusion by the Proton-Proton Chain

**Step 1**
Two protons fuse to make a deuterium nucleus (1 proton and 1 neutron). This step occurs twice in the overall reaction.

**Step 2**
The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step also occurs twice in the overall reaction.

**Step 3**
Two helium-3 nuclei fuse to form helium-4 (2 protons, 2 neutrons), releasing two excess protons in the process.

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 protons</td>
<td>4He nucleus</td>
</tr>
<tr>
<td>2 gamma rays</td>
<td>2 positrons</td>
</tr>
<tr>
<td>2 neutrinos</td>
<td>Total mass is 0.7% lower</td>
</tr>
</tbody>
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\[ E = mc^2 \]

### Thought Question

What would happen inside the Sun if a slight rise in core temperature led to a rapid rise in fusion energy?

A. The core would expand and heat up slightly  
B. The core would expand and cool  
C. The Sun would blow up like a hydrogen bomb

**Solar thermostat keeps burning rate steady**
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 a star Sun?

Problem:
Energy created in interior of a star
How does it get to the surface?

Radiation

The Electromagnetic Radiation (light) produced by the hot gas in the center is absorbed by the surrounding gas, and then re-emitted. So a single photon is continually absorbed and re-emitted. The entire journey can take a million years.

Convection

When radiation is ineffective in transporting energy, Convection (rising hot gas) takes energy to surface
How we know what is happening inside the Sun?

We learn about inside of Sun by …

• Making mathematical models
• Observing solar vibrations
• Observing solar neutrinos

Measuring Vibrations on the Sun

We can measure vibrations by measuring the doppler shift of gas on the Sun.

Sun is ringing like a bell

Patterns of vibration on surface tell us about what Sun is like inside

Data on solar vibrations agree very well with mathematical models of solar interior

We find that in different layers in the Sun, both radiation and convection are important for bringing energy from the core to the surface.
Neutrinos created during fusion fly directly through the Sun. Neutrino is massless (or almost massless particle) without charge that moves at the speed of light. They do not interact with matter easily, and can pass through the Earth.

Observations of these solar neutrinos can tell us what’s happening in core.

Solar Neutrinos

Solar neutrino problem:

Neutrino telescopes are placed underground to shield them from other types of cosmic rays.

50 trillion neutrinos from the sun pass through your body every second.

A few neutrinos can be absorbed by a neutron, converting the neutron into a proton and electron. Other neutrinos directly interact with electrons. As the electrons move through the water, they produce flashes of light.

Early searches for solar neutrinos failed to find the predicted number.

More recent observations find the right number of neutrinos, but some have changed form.

Sudbury Neutrino Observatory, more than 2 km underground
Sphere contains 1000 tons of ultrapure heavy water.

What causes solar activity and how does it affect the Earth?

Stereo Observes the Sun

**Sunspots**

- Are cooler than other parts of the Sun's surface (4000 K)
- Are regions with strong magnetic fields

**Zeeman Effect**

- We can measure magnetic fields in sunspots by observing the splitting of spectral lines

- Outside a sunspot, we see a single spectral line...

- ...but the strong magnetic field inside a sunspot splits that line into three lines.

- Charged particles spiral along magnetic field lines

- Magnetic field lines represent the directions in which compass needles would point.

- Lines closer together indicate a stronger magnetic field.
Loops of bright gas often connect sunspot pairs.

Magnetic Activity on the Sun

**Corona** appears bright in X-ray photos in places where magnetic fields trap hot gas. Dark spots are coronal holes - which eject fast solar wind.

**Solar flares** are explosions that send bursts of X-rays and charged particles into space. Energy of the flares can reach billion's of megatons, heating gas to 100 million Kelvin in minutes. Associated with sun spots.

**Coronal mass ejections** are bursts of energetic charged particles out through the solar system. Are often related to solar flares and prominences.

Magnetic activity also causes **solar prominences** that are associated with pairs of sun spots. These processes may heat corona and help lead to solar wind.
Stereo Observes a Solar Prominence

http://www.spaceweather.com/archive.php?view=1&day=08&month=10

Sunspot cycle has something to do with winding and twisting of Sun’s magnetic field.
Field reverses every 11 year.
Luminosity of Sun doesn’t change much, around 0.1% over last 30 years.

Flares have a scale A, B, C, M, X. The Halloween storm was rated X28
Overview: How Does a Star Work?

Energy produced in the core of star by nuclear fusion

Energy is transported from the center to the surface of the star by light (electromagnetic radiation) or by convection (movement of hot gas). Light is continually absorbed and re-emitted in the hot gas surrounding the core.

When energy reaches the surface and heats the outer gas. The hot gas glows, producing the light that illuminates and heats the Earth (and for other stars - the star light we see in the sky).

A small fraction of solar energy released in a solar wind, solar flares and CMEs. Heating of the Corona to a million degrees leads to the solar wind.

Summary

The structure and energy source of a star, using the Sun as an example:

What are the different layers of the Sun?
How does nuclear fusion produce energy and helium in the Sun?
How does that energy get to the photosphere of the Sun?
Measurements of the inner processes in the Sun
Solar activity.

Universal Laws

The conservation of energy, momentum and angular momentum apply everywhere in the Universe.

Astronomers use these laws to understand the energy source of stars, the dynamics of galaxies, the formation of stars, and just about every phenomena observed in the Universe.

Theories and Laws

What is the difference between a theory and a law?

Common misconception:

Theories are unproven

Laws are proven

This explanation confuses a hypothesis and a theory.
Physical Laws

A mathematical or logical relationship:

Newton’s Three Laws
Law of Universal Gravity

Are these proven?

No: we now know they are approximations

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Theories

Theories try to explain and relate a disparate group of observations.

Examples:

Newton’s laws form a theory of motion which explains the motion of bodies on Earth, and the motions of planets in our solar system.

**Application and predictions:** motions of airplanes and aerodynamics, motions of satellites, motions of planets around other stars, interacting galaxies, …

Theory of electromagnetism explains electricity and magnetism

**Application and predictions:** power generation, radio waves

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Can Theories Be Proven?

They can be *tested*, and disproven, but they can’t be tested in every instance. A theory cannot be proven like a mathematical theorem.

A theory may turn out to be a useful approximation, example:

Newton’s laws are an approximation: they are superseded by Einstein’s theory of relativity on large scales and quantum mechanics on small scales.

However, these laws are extremely useful as long as we know when and where they can be applied.