A100–Exploring the Universe: How Stars Work

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Exam scores posted in Mastering

Exam keys posted on class website, see
http://www.astro.umass.edu/~weinberg/a100/exams.html
Announcements

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Today: More on stars

- Finish: how stars work
- What is the Sun’s structure?
- Properties of Stars
  - How do we measure stellar luminosities?
  - How do we measure stellar temperatures?
  - How do we measure stellar masses?

Read: Chaps 14, 15
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Today: More on stars

Finish: how stars work
What is the Sun’s structure?

Properties of Stars
- How do we measure stellar luminosities?
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Questions?

Read: Chaps 14, 15
What do they have in common??

Read: Chaps 14, 15
Maxwell distribution & exam grades

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Distribution
Maxwell distribution & exam grades

Cumulative Distribution

Announcements
- Exam questions
- Grav equilibrium
- P-P fusion reaction
- Mass to energy
- Energy transport
- Solar model
- Solar dimensions
- Thought question
- Inside the Sun
- Helioseismology
- Neutrinos
- Surface of the Sun
- Limb darkening
- Corona
- Sunspots
- Magnetic fields
- Solar dynamo
- Solar Components

Read: Chaps 14, 15
Maxwell distribution & exam grades

What do they have in common??

![Graph showing Maxwell distribution]

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10/11/12 – slide 3
What do they have in common??

Let’s roll some dice!

1. Choose some number of dies (1,2,3,4...)  
2. Roll and add up faces  
3. Repeat Step 2 and make a histogram
If you drop a rock from a great height, about how fast will it be falling after 5 seconds, neglecting air resistance?

A) 10 m/s
B) 50 m/s
C) 15 m/s
D) It depends on what shape it is.
E) It depends on how heavy it is.
Which of the following statements is not one of Newton’s laws of motion?

A) The rate of change of momentum of an object is equal to the net force applied to the object.

B) In the absence of a net force, an object moves with constant velocity.

C) What goes up must come down.

D) For any force, there always is an equal and opposite reaction force.

E) All of the above are Newton’s laws of motion.
When an electron in an atom goes from a higher energy state to a lower energy state, the atom

A) can emit a photon of any frequency.
B) emits a photon of a specific frequency.
C) can absorb a photon of any frequency.
D) absorbs a photon of a specific frequency.
E) absorbs several photons of a specific frequency.
The force of gravity is an inverse square law. This means that, if you double the distance between two large masses, the gravitational force between them

A) weakens by a factor of 4.

B) weakens by a factor of 2.

C) strengthens by a factor of 4.

D) is unaffected.

E) also doubles.
Gravitational equilibrium

Energy provided by fusion maintains the pressure
P-P fusion reaction

3 steps in a fusion reaction

1. Step 1

Read: Chaps 14, 15
3 steps in a fusion reaction

\[ \begin{align*}
\text{Step 1: } & \quad 1H + 1H \\
\text{Step 2: } & \quad 2H + 3He \\
\text{Step 3: } & \quad \gamma 
\end{align*} \]
P-P fusion reaction

3 steps in a fusion reaction

$^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 1^1\text{H} + 1^1\text{H}$

Step 3
Mass is not always conserved.

\[ E = mc^2 \]

- **electron volt**: energy an electron gains if it moves 1 cm through a 1 volt field (= \(1.6 \times 10^{-19}\) Joules)
- 14 electron volts to remove an electron from a hydrogen atom
- Energy equivalent of one atomic mass unit (mass of proton & neutron) is 931.4 MeV
- An electron has a mass which is roughly 1/1870 that of the proton
- If an electron and a positron annihilate the combined mass would be 2 \(\times\) 1/1870 of a proton or 1.02 MeV

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Certain combinations of protons and nuclei are less than their sum of parts.

Can liberate energy by assembling a more massive nucleus!
Elements below iron (Fe) can from by fusion

Elements below iron (Fe) cannot (radioactive decay)

Most elements heavier than helium are made in stars!

Read: Chaps 14, 15
How does energy get to surface?

- Fusion temperature: 10 million degrees
- Outer Sun: 5000 degrees
Three mechanisms for energy transport

1. *Conduction*: heat flows from hot to cold
   - Energy transferred from atom to atom
   - E.g. handle of frying pan on stove

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1. *Conduction*: heat flows from hot to cold
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2. *Radiative diffusion*: high energy photons interact with matter give up some of their energy, replenishing local heat supply
   - Random walk [movie]
   - Takes $10^7$ (10 million) years for photon generated to get out!
   - Photons can also provide some of the pressure to support star against its own gravitational pull
3. *Convection*: energy carried from hotter regions below to cooler regions above by bulk buoyant motions of the gas.

- Hot blobs of gas rise, release energy
- Cool blobs of gas fall
- Example: coffee cup with milk …
3. **Convection**: energy carried from hotter regions below to cooler regions above by bulk buoyant motions of the gas.

[movie]
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Instant coffee with soymilk

[movie]
• Fusion: radii < 0.25\(R_\odot\)
• Radiative diffusion: 0.25\(R_\odot\) < radii < 0.71\(R_\odot\)
• Convection: 0.71\(R_\odot\) < radii < 1.00\(R_\odot\)
• Solar wind: \(R_\odot\) < radii

Read: Chaps 14, 15
Solar dimensions

- **Radius**: $6.9 \times 10^8$ m (109 Earth radii)
- **Mass**: $2.0 \times 10^{30}$ kg (300,000 Earth masses)
- **Luminosity**: $3.8 \times 10^{26}$ watts
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
What would happen inside the Sun if a slight rise in core temperature led to a rapid rise in fusion energy?

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How do we know what is happening inside the Sun?

Read: Chaps 14, 15
How do we know what is happening inside the Sun?

- Making mathematical models
- Observing solar vibrations
- Observing solar neutrinos

Read: Chaps 14, 15
Patterns of vibration on surface tell us about what Sun is like inside.

Gas is vibrating outward in blue regions... and inward in red regions.
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.
Neutrinos from fusion fly directly through the Sun

Solar neutrinos can tell us what's happening in core

Read: Chaps 14, 15
Solar neutrino problem:

- Early searches for solar neutrinos failed to find the predicted number.
Solar neutrino problem:

- 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.
Surface of the Sun

Three regions:

- **Photosphere**— most of Sun’s luminosity
- **Chromosphere**— Above the photosphere
- **Corona**— Superheated region above the Chromosphere

Read: Chaps 14, 15
Three regions:

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  Above: photons stream without interacting
  
  Below: photons interact with solar material

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- **Corona**— Superheated region above the Chromosphere
  Origin of the solar wind, protons that have escaped the Sun.

Read: Chaps 14, 15
Limb darkening

- Photosphere–Sun appears darker around the edge
- Photons from *limb* from greater height in atmosphere
- Upper photosphere/lower chromosphere is cool

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Image of Sun during total eclipse

Material streams away from Sun

Narrow transition between chromosphere and corona
Sunspots

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Sunspots

Cycle 23 Sunspot Number Prediction (October 2002)

[Image of the Sun with sunspots]

Read: Chaps 14, 15
Sunspots are regions of high magnetic field
Zeeman splitting
Consequences: magnetic fields!

- Generated by moving charges: electric currents
- Continuous loops of lines of force that have both tension and pressure (like rubber bands)
- Can be strengthened by stretching them, twisting them, and folding them back on themselves.
- This stretching, twisting, and folding is done by the fluid flows within the Sun!
Magnetic field is trapped in ionized gas (*plasma*)

Rotating Sun winds up the field lines
Solar dynamo

- TRACE solar mission (NASA)
- SOHO solar mission (ESA)
- UV image

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Solar Wind: a flow of charged particles from the surface of the Sun.
Corona: outermost layer of the solar atmosphere, $T \approx 1$ million K
Chromosphere: middle layer of the solar atmosphere, $T \approx 10^4$–$10^5$ K
Photosphere: visible surface of the Sun, $T \approx 6,000$ K
**Convection zone**: energy transported upwards by rising gas
Radiation zone: energy transported upward by photons
Core: energy generated by nuclear fusion, $T \approx 15$ million K