Lecture 17
The Solar Interior

Pressure Balance: Perfect Gas
Energy Balance: Convection
Solar Interior Model
Helioseismology

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Astro 100 Lecture 17

Reprise - Fusion Energy

• **Products:**
  – "neutrino" massless (?), chargeless particle carrying energy
  – "gamma ray" photon of very high energy (short wavelength) light
  – $e^+$: "anti-electron", or "positron", immediately makes more energy by "annihilating" with electron:
    $$e^+ + e^- \rightarrow \text{gamma ray}$$

• **Hydrogen Fusion Bottom Line:**
  $$4 \ H \rightarrow \ He + \text{Energy} + \text{Neutrinos}$$

Figure 5.11, p160, Arny
H Fusion Hypothesis Verification

• Indirect: energy leaking out of Sun is about the right amount (takes ~100,000 yrs to get out)
• Direct: Neutrinos
  – Very elusive particles. Interact so infrequently with matter that escape interior of sun immediately
  – Also go right through most telescopes! Neutrino telescopes: large vats of pure elements: detect few/day events out of huge number
  – Observations see 1/3-2/3 of those expected. Now understood based on neutrinos having a small mass, and "change flavor" during escape from Sun

Physics of Stars

*What holds them up?*

High temperatures in sun (and other stars) mean material is gaseous throughout (exceptions later).
• It turns out gas is much easier to understand than solid or liquid, so can make simple "model" of sun which matches all properties very well
• Basic principle: equilibrium. The structure of the Sun seems to have been pretty stable over 4 Gyr, so all forces must be pretty close to balance
Rule 1: Pressure Balance

- **Pressure Balance** ("hydrostatic equilibrium").
  - At every depth, the weight of the overlying material is exactly balanced by the gas pressure.
  - Otherwise the material would be rapidly accelerated, collapsing or blowing up the star in a few days.

- **Equation of State.**
  - This tells how the gas pressure depends on its composition, temperature, and density:
    - "Perfect Gas": in the sun the pressure is proportional to the temperature and density (particles/volume)
    - There are other, more exotic equations of state, governing stars more exotic than the Sun

Basic Principle #1

- This already illustrates the basic principle:

  *The sun does not collapse under its own gravity because it is hot enough inside that the pressure balances gravity.*

  But how hot is it?
Rule 2: Energy Balance

- **Temperature Balance** ("thermal equilibrium").
  - At every depth, the loss of heat due to cooling is exactly balanced by heating from the inside.
  - Otherwise the material would heat up or cool down, which would mess up the pressure balance in a few thousand to a million years.

- **Energy Generation**
  - This tells how energy lost to the outside is replaced.
  - In the sun, this is the "proton-proton" variety of hydrogen fusion.
  - Depends very sensitively on temperature. (There are other varieties active in other stars.)

Energy Balance - Continued

**Energy Transport** (how good is the insulation)
This tells how easily the heat flows from the inside to the outside. Depending on conditions,

- **Conduction.** Hot atoms run into cool atoms, speeding them up (e.g. touching hot stove). Not important in solar interior.
- **Radiation.** Hot gas emits light, which is absorbed by cool material. (e.g. how sun heats up earth). Important.
- **Convection.** Hot gas is light, cool gas heavy. If gas "turns over", it carries heat (e.g. "heat waves" above a hot highway, cumulus clouds). Takes over when radiative transport is not enough.
Basic Principle #2

- So the bottom line is,

*as long as fusion continues in the center of the sun, it replaces the heat lost to the outside, keeping the temperature high enough that it does not collapse under its own gravity.*

Interior of the Sun

Can calculate physical state of *interior of Sun* based on these principles:

- **Center:**
  - Temperature $15.8 \times 10^6$ K
  - Density $162$ gm/cm$^3$ (162x water)
  - % H: 34% (down 2x from start at 70%)
  - %He: 64%

- **“Core”:**
  - $\frac{1}{2}$ of nuclear fusion (mostly proton-proton) within inner 10%

- **“Envelope”**
  - Radiative out to 70%
  - Convective outer envelope - agrees with surface we see!
Verification: Helioseismology

- **Helioseismology.** Can see “ringing” of sun as sound waves propagate through it!
  - Brightness variations
  - Velocity variations (Doppler effect shifting of absorption lines)

- **Observatories**
  - Global Oscillation Network Group (GONG)
    - 6 ground-based dedicated telescopes
  - Michelson Doppler Imager (MDI)
    - On SOHO satellite

Super-Kamiokande Neutrino Telescope

\[ \nu + e^- \rightarrow \nu + e^- \]

50,000 tons H\textsubscript{2}O
SAGE Neutrino Telescope

50 tons Gallium

$^{71}\text{Ga} + \nu \rightarrow ^{71}\text{Ge} + e^-$

Neutrino Image of the Sky

the Sun
Perfect Gas Pressure

Pressure = constant x (Number of particles/ volume) x Temperature

Interior of the Sun
Core and Envelope

Figure 5.11, p153, Arny

Helioseismology

Figure 5.2, p155, Arny
GONG