Chapter 09: The Sun

Notes and Sketches

9.1: The Sun in Bulk

- Pretty average, as far as stars go
- Understand this star, understand many stars (but not all stars)

Overall Structure

- All gas: No solid composition
- Layered structure (not like terrestrial layers, though)
- Differential rotation (similar to jovian planets)

Luminosity

- How much total energy emitted per second by a star (Joule/sec = Watt)
- More energy, greater luminosity
- Solar constant: How much energy strikes 1 m^2 every second where we are (distance from sun = 1AU)
- Solar constant = 1400 Joules of energy every second per square meter
- Luminosity: Multiply 1400 J/s·m^2 by total area of shell with r = 1AU
- Luminosity = $4x10^{26}$ J/s = $4x10^{26}$ Watts

9.2: The Solar Interior

- We cannot see inside the sun
- Photosphere = layer we can see (because it emits visible light)
- Photosphere is not the only layer, or even the "top" layer

Modeling the Structure of the Sun

- Many properties remain (virtually) constant over long periods of time: mass, radius, temperature, luminosity
- Why? If something remains unchanging, it is in an equilibrium state

Hydrostatic Equilibrium

- Gravity (wants to pull mass in (contract)) balances gas pressure (wants to expand mass outward)
- How much mass determines how much gravity: This determines how much outward pressure there must also be
- How much pressure determines the density and pressure inside the sun
- Density and pressure predict observable properties
- Scientific method: Observe and refine model

Information On the Solar Interior

- Helioseismology: Pressure waves on the interior resonate back and forth through the interior, reflecting off the photosphere
- This can be observed through Doppler shifts on the surface
- SOHO: SOlar and Heliospheric Observatory orbiting sun since 1995
- Enough data from enough sources over enough time to know conclusively about the density and pressure internal to the sun

Energy Transport

Radiation Zone

- Start at the center and work towards the surface of the sun
- Hot, hot core: Too hot for electrons to stay bound to nuclei, so no absorption/emission by electrons (core is transparent to e·m radiation)
- Farther from core, temperature decreases: Electrons can remain bound to nuclei
- Bound electrons can absorb radiated energy
- Increasing opacity with distance from center: More and more energy absorbed

Convection Zone

- If radiated energy is absorbed in the interior, how does any energy escape?
- Convection: Energy transfer via bulk motion of the medium
- Move the energy by moving the actual mass: Warm rises, cold sinks (whether you are talking about water boiling in a pan, the Earth's atmosphere, or the interior of the sun)
- Layers of convections cells: Progressively smaller with increasing distance from core
- Convection stops at photosphere: Density too low to maintain convective circulation
- Radiation takes over as energy transfer mechanism: Opaque back to transparent

Evidence for Solar Convection

- Indirect: Computer models are consistent with observed energy rates
- Direct: Granulation = appearance of convection pattern on solar surface
- Areas about 1000 km across vary in color (temperature)
- Bright = hot (rising), darker = cooler (falling)
- Doppler shift confirms direction of motion: Bright = blueshifted (approach = rising), dark = redshifted (receding = falling)
- Supergranulation: Even larger (30,000 km across) pattern below the granulation pattern

9.3: The Solar Atmosphere

- Use spectroscopy to determine composition: Hydrogen, helium (trace amounts of 65 additional elements as well)
- Tells us literally only about the layer we observed directly
- Infer that composition does not change substantially through interior
- Exception: Core composition cannot be constant (nuclear fusion, by definition, results in a continuously changing core)

The Photosphere

- The layer we see: About 500 km thick (which is really pretty thin)
- Average temperature 5780K
- Not the hottest layer, just the temperature of the layer we can see

The Chromosphere

- A little cooler than the photosphere (not much)
- About 1500 km thick
- Low density means not normally visible (can be seen during eclipses)
- Looks pink because H-alpha line dominates
- Stormy layer: Spicules (jets) erupt near edges of supergranules

The Transition Zone and Corona

- Total eclipse: Cover the solar disk, cover the chromosphere and corona appears
- Transition zone: Temperature rises very dramatically (increases from 5000K to ≈1,000,000K over 5000 km distance)
- Corona: Temperature stays relatively constant at about 3,000,000K
- High temp results in ionized gases: Spectra confirm this
- Temperature rise not yet understood: Secondary heat source?

The Solar Wind

- Radiation: You know the energy escapes (at light speed, literally) because you can step outside and enjoy the sunshine

Notes and Sketches

- Radiation carries no particles of matter, just pure energy Particles are ejected as well: Protons and electrons
- Corona is hot enough: Particles have enough energy to escape sun's gravity
- Sun is losing mass: About 1 million tons every single second
- Sun has a lot of mass to lose: About 0.1% total mass lost since formation

9.4: The Active Sun

Sunspots

- Size varies: May be up to 10,000 km across
- Number varies: May be many, may be few, may be none at all
- Dark color indicates cooler temperature: Coolest at center (≈4500K), heating up towards edge (≈5500K)
- Sunspot observation demonstrates differential rotation

Solar Magnetism

- The sun has a magnetic field (stronger than Earth's magnetic field)
- Sunspots are connected to the magnetic field: Spot fields are about 1000x stronger than surrounding field
- Field causes cooling? Hypothesis is that strong field disrupts typical convective cycle, so spot is cooler than surrounding area
- Sunspot pairs: Just like a magnet has a N and S pole, spots come in magnetic pairs (one N, the other S)
- Strong magnetic field loops from N to S spot

Random But Not Random

- Spots may look random, but there is underlying order based on sun's magnetic field
- Differential rotation distorts sun's magnetic field
- Faster equatorial rotation "pulls" field in direction of motion
- In the N hemisphere, N ends up facing E
- In the S hemisphere, N ends up facing W
- Spot pairs always face the same direction in the same hemisphere

The Solar Cycle

- Individual spot life spans cannot be predicted in advance: Maybe 1 day, maybe 100
- Long-term activity patterns can be extracted
- Sunspot Cycle: Count the number of (distinct) spots observed monthly, trend emerges with 11-year period (maximum to maximum)
- Solar Cycle: 22-year period for sun to reverse magnetic polarity
- Exceptions to the rule: Maunder Minimum (1645-1715) period of almost zero sunspot activity (no data on sun's magnetic field possible at this time) coincides with period of unusually cold N hemisphere weather
- No answer to explain connection

Active Regions

- Photosphere surrounding groups of sunspots can be suddenly, violently active: Energetic particles ejected into solar corona
- Solar Prominence: The material ejected from an active region; shape determined by magnetic field, typically loops from following magnetic field lines
- Solar Flare: Huge, fast, hot ejection of material into space; origin in lower atmosphere, can reach 100,000,000K (hotter than solar core)
- Coronal Mass Ejection: Bubble of ionized/magnetized gas detaches from corona; number of CMEs increases with sunspot activity; potential to disrupt e·m fields on Earth

Notes and Sketches

The Sun in X-Rays

- Higher temperature corresponds to shorter wavelength (higher frequency)
- The hot corona glows in the x-ray range of wavelengths
- Coronal Hole: If magnetic field lines extend into space, particles can escape by following field lines (lines that loop back to surface are not escape routes)

The Changing Solar Corona

- Sunspot minimum: Corona is pretty uniform
- Sunspot maximum: Irregular, asymmetric shape
- It all ties back to the magnetic field

9.5: The Heart of the Sun

Nuclear Fusion

- The only possible way to account for the amount of energy produced by the sun
- In general: Two nuclei are forced to join together, to form a third, different nucleus
- Energy is released according to $E = mc^2$
- As fusion occurs in the sun's core, it slowly loses mass (that is converted to energy)

The Strong Nuclear Force

- To build nuclei out of protons and neutrons, you cannot rely on gravity and electrostatic forces
- You need a force that is very, very strong over very, very short distances
- The strength must drop off very, very quickly with increasing distance
- Nuclear strong force: Binds protons and neutrons in nucleus, prevents electrostatic repulsion from blasting the protons apart from each other
- Strong force is 100x stronger than electrostatic force, 10^{39}x stronger than gravity
- Electrons are not subject to the strong force

Like Repels Like

- If you can get two protons closer than 10^{-15}m together, the e-m repulsion will be less than the strong attraction
- Get them that close together, and they will fuse to form a new nucleus
- The trick is getting them that close together: Collide particles at high speed
- The center of the sun is perfect: High temperature means particles are moving very, very fast; high pressure means they are very likely to collide with each other

The Proton—Proton Chain: Step 1

- proton + proton = deuteron + positron+ neutrino + gamma radiation
- Deuteron: One proton bound with one neutron (net charge = +1)
- Positron: An anti-electron (same mass as an e-, but charge = +1)
- Neutrino: Neutral, tiny, tiny, tiny mass
- The books have to balance perfectly: total (mass + energy, charge) before has to exactly equal total (mass + energy, charge) after

The Proton-Proton Chain: Step 2

- deuteron + proton = helium-3 (two protons, one neutron)
- positron + electron = gamma radiation

Proton-Proton Chain: Step 3

- helium-3 + helium-3 = helium-4 (2 protons, 2 neutrons) + proton + proton
- Those last two protons will go on to collide with something else, ending up back at step 1 or step 2

Notes and Sketches

Hydrogen Into Helium

- So, skipping the intermediate steps, at its core, the sun fuses hydrogen into helium
- 600 million tons of mass per second are converted
- At that rate, the sun will only last another 5 billion years

Observations of Solar Neutrinos

- Neutrinos are magic!
- No they aren't. But they are evidence of fusion at the sun's core
- Neutrinos do not interact with anything (well, hardy anything), they just zip out into space, carrying energy

The Solar Neutrino Problem

- Problem 1: Building a detector that can actually see neutrinos.
- Solution 1: This is harder than it sounds, but isolate a large quantity of salt water.
- Problem 2: The sun does not appear to be aware that it ought to be emitting many, many more neutrinos than it actually is.
- Solution 2, Part A: Double check your equipment. Make sure your detector is functioning properly.
- Solution 2, Part B: Hypothesize that, if neutrinos had mass, there might be different types of neutrinos. Design an experiment to look for these other types of neutrinos, and when you find them, go back to looking at the sun. Find the missing neutrinos.
- Solar neutrino problem solved: The scientific method wins yet again!

Notes and Sketches