

Astronomy 162, Week 5

Energy and the Sun

Patrick S. Osmer

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Review

- In the previous lecture, we discussed:
 - the enormous power radiated by the Sun
 - possible energy sources
 - how Einstein's equation, $E = mc^2$ provided a solution
 - the proton – proton reaction as the main energy source for the Sun

Today

- Consider how we can determine the internal structure of the Sun, i.e.,
- Construct a solar model

Interior of Sun

- How do we know interior of sun is hot enough for nuclear reactions to occur?
- What will happen to the sun as it uses up its hydrogen?

Key Principles

- The sun is a gas throughout (not liquid, not solid)
- Sun's interior is described by ideal gas law:
 - Pressure (P) is proportional to density (N) times temperature (T)
 - $P = N k T$ (k is constant of proportionality)
- Note: these seemingly simple statements are fundamental to understanding structure of stars
- Ideal gas law applies to most stars on main sequence
 - but not to white dwarfs or cores of red giants
 - radiation pressure important in massive stars

The sun is stable

- Also simple and fundamental statement
- Sun is in hydrostatic equilibrium
 - not shrinking or expanding
- This means the gas pressure balances the pull of gravity throughout the star
 - contest of gravity and pressure is a tie at this stage
 - see Fig. 18-3

Sun is in thermal equilibrium

- Its temperature is not changing
- Energy being radiated (lost) at surface is balanced by energy generated in interior
- This means temperature is highest at center, coolest at surface
 - if temperature were not high at center, surface would cool off

Heat flows from center to surface

- Heat always flows from hotter to cooler regions
- Solar heat is carried by
 - radiation
 - convection
 - (conduction is not important in sun)
- Convection
 - think of motions in boiling water
 - circulating currents of gas carry heat outward
- Radiation
 - also carries heat outward
 - not as effective as convection because of high opacity. Light takes 10 million years to escape, instead of 2 sec, as for neutrinos

Model Stars

- By applying
 - key principles
 - additional knowledge of physics
 - numerical techniques
 - differential equations
 - computers
- we can construct detailed models of stellar interiors

Models, cont.

- Start with
 - hydrostatic equilibrium
 - ideal gas law
 - thermal equilibrium
 - physics of heat transport
 - opacity of matter in interior
 - nuclear energy rates

Approach

- Find a numerical solution for values of
 - temperature
 - pressure (or density)
 - mass
 - luminosity
- for all distances from center to surface
- result is a model for the sun or stars

Results

- Central temperature of sun is 15 million deg
- Central density is 160 times that of water
- Nuclear energy generated in inner 30% of sun
- Radiation carries the energy for inner 70% of sun
- Convection, for the outer 30%
- See table 18-2, Figs. 18-4, 18-5

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Solar Interior - Theory and Obs.

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Model Stars

- Have covered main physical principles for interiors of stars
- Stars are powered by nuclear fusion at their centers
- We can compute models of stars
- Today - continue discussion of models, then discuss observational tests of models

Nuclear thermostat

- Nuclear reactions are very sensitive to temperature
 - small increase in temperature produces large increase in reaction rates and energy production
 - this is good! It provides stability to the star
 - If core temperature too low, gravity forces it to contract, temperature goes up, more energy produced, star gets back in balance
- If core temperature too high, increased gas pressure causes expansion, temperature drops, energy production drops, star gets back in balance
- Thus, nuclear reactions provide both energy and stability to the star (at this stage)

Russell-Vogt Theorem

- Provides concise statement of key points and explanation of main sequence.
 - Theorem: If star is in hydrostatic and thermal equilibrium, and derives all its energy from nuclear sources, then its structure is completely determined by its mass and the distribution of chemical elements in its interior.

What does it mean?

- If a group of stars has the same composition, then their structure will be determined only by their mass.
 - The models will show that the most massive stars are the hottest and most luminous
 - The least massive will be the coolest and least luminous
 - In fact, the stars will lie on the main sequence (Stromgren 1930)
- In this way, we can account for about 90% of all stars.
 - Recall the mass-luminosity relation and the properties of the main sequence!!!
 - **THE MAIN SEQUENCE IS A MASS SEQUENCE!**
 - low mass, low luminosity
 - high mass, high luminosity

What about stars not on the main sequence?

- What about
 - supergiants
 - giants
 - white dwarfs
 - According to Russell-Vogt theorem, either they have different composition, or
 - they don't get their energy from nuclear sources
-
- This shows conceptual power of Russell-Vogt theorem
 - Two parts to the composition question
 - Stars can have
 - 1) different initial composition, or
 - 2) consume the hydrogen in their center
 - Both effects are important in understanding different types of stars

Checking the theories

- How do we know the theory is correct?
 - We cannot see into the sun (in visible light)
- What tools do we have? Two:
 - neutrinos
 - pulsations

Neutrinos

- Produced in nuclear reactions at core of sun
 - ghostly particles, pass right through the sun (and us) as if it weren't there. Could pass through a light year of lead
 - carry energy
 - are numerous (a trillion pass through us per second)
 - provide a direct probe of the core (which we can't see in visible light)

How to detect neutrinos?

- It's really hard! But possible
- Neutrino observatory
 - Put 400,000 liters of cleaning fluid one mile underground in a mine in S. Dakota
 - Must go underground to avoid cosmic rays
 - Wait for solar neutrinos to convert chlorine atoms to radioactive argon atoms
 - Detect argon atoms

Neutrino Obs., continued

- Neutrino observatories very unlike optical telescopes and observatories
- Neutrinos, very occasionally, do interact with matter
- Solar neutrinos produce about 1 argon atom every three days, which, amazingly, can be detected in the cleaning fluid

The solar neutrino problem

- Rate of detection was 1/3 that predicted by standard models of the sun
- What was going on?
- This was one of the major research problems in astrophysics
- A solution has emerged in the last few years

How to proceed?

- One possibility –
 - If center of sun is slightly cooler than predicted, then it would produce fewer neutrinos
- Or, other physics is involved
 - neutrinos may change their type (and have mass, which will be important for the dark matter problem we'll take up later)
- First, let's check on the solar model

Solar pulsations and seismology

- Pulsation - periodic expansion and contraction
- Remember I said the sun is stable
 - well, it is in general, but not at the smallest scale
 - it has small pulsations of 4 - 10,000 km on time scales of 2.5 - 11 min.
- Why is this important?
- Recall how seismology works on earth
 - study of waves allows us to determine structure (earthquakes are an extreme example)
- Same principle applies to sun

Solar seismology

- Can deduce structure of sun from the waves that go through it
 - they take about an hour
 - give direct measure of structure of sun
 - has similarity to CAT scans in medicine

Observations

- GONG project (global oscillations network)
 - See <http://gong.nso.edu/>
- Array of telescopes spread around the world to give 24 hour / day coverage of the sun
- Observe the pulsations with very sophisticated instruments
- Apply very sophisticated math. to deduce structure.

Results

- Find convection zone extends 30% in from surface, not the 15-20% that used to be thought
- Helium abundance is as expected in interior
- Outer 30% rotates at same rate as surface (slower at poles than equator)
- Inner part rotates like a solid body

- Latest results confirm temperatures predicted by models from surface to about 95% of way to center to within 0.1%(!)
 - (this is astoundingly good agreement)
- Neutrino problem seems to be in the physics of neutrinos, not the solar model, which is confirmed remarkably well

Solar Neutrino Mystery Solved?

- New solar neutrino observatories have contributed crucial results
 - Super-Kamiokande in Japan
 - Sudbury (Ontario) Neutrino Observatory (SNO)
 - <http://www.sno.phy.queensu.ca/>
 - Uses “heavy” water to detect neutrinos of different types. See www.physicstoday.org/pt/vol-54/iss-8/p13.html

Neutrinos change type

- After the neutrinos are produced in the sun, some change type en route to us.
 - Thus, they were missed by the first detectors
 - It appears there are three different types of neutrinos, and 2/3 were being missed
 - This means new physics
 - But confirms our model of the sun
 - The sun is powered by nuclear reactions

Update

- OSU Astronomy Prof. Marc Pinsonneault is a world expert on solar models. He informs us that the SNO data have confirmed:
 - the three different types of neutrinos
 - the proton-proton reaction does power the Sun
 - the central temperature of the Sun to within 0.3%
- New research problem:
 - new models of the solar atmosphere indicate the C, N, O abundances are less than previously thought
 - if so, then the solar models and GONG data don't agree so well
 - Stay tuned. There will likely be future developments in this subject

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Evolution of Stars

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Summary of Stellar Structure

- Have considered gravitational, thermal, and nuclear energy as they affect the sun
- Used conservation of mass and energy
 - $E = mc^2$
- Sun gets its energy from nuclear fusion
 - Proton-proton cycle converts four hydrogen atoms to one helium atom, releases 0.7% of rest mass as energy
 - Used principles of pressure and thermal equilibrium to compute solar model
 - $P(r)$, $T(r)$, $L(r)$, $M(r)$
 - Russell-Vogt theorem & interpretation of main sequence
 - Checked theories by obs. of neutrinos and pulsations of sun

CNO cycle

(Carbon, nitrogen, oxygen)

- In sun, proton-proton reaction dominates
- In more massive stars (which have higher central temperatures), another reaction, the CNO cycle provides the energy
- CNO cycle
 - still converts hydrogen to helium
 - but uses C, N, O as catalysts
 - rate increases very rapidly with temperature
- (Show viewgraph on CNO cycle here)

Summary of Energy Generation

- Conversion of hydrogen to helium provides most (80 – 90%) of energy during a star's lifetime
 - H is most abundant element, produces most energy per unit mass
 - Proton-Proton cycle dominates in stars like Sun
 - CNO cycle in more massive star
 - Strong temperature dependence of reactions helps maintain stability

Stellar Lifetimes

- Recall mass-luminosity relation
 - Massive stars very luminous
 - Low mass stars very dim
- Which have shortest lives?
 - High-mass stars
- Why?
 - Luminosity per mass much greater, consume their nuclear fuel much faster

Numerical Examples

- Mass-luminosity relation
 - Lum. proportional to mass to 3.5 power
 - Available fuel proportional to mass
 - Lifetime goes as (1/mass) to 2.5 power
- Sun lives for about 10 billion years
 - 0.5 solar mass star, 200 billion years
 - 25 solar mass star, 3 million years

Evolution on Main Sequence

- Hydrogen is converted to helium in core of star
- Temperature increases
- Nuclear reaction rates increase
- Luminosity increases

Fig. 21-1, Changes in the Sun's composition

End of main sequence phase

- When all hydrogen in core is converted to helium, nuclear reactions in core stop
- Then the pure helium core starts to contract
 - it is not producing energy
 - cannot balance heat loss, maintain pressure
 - has to give up gravitational energy to produce heat

Evolution to red giants

- As helium core contracts, structure of star changes dramatically
 - Temperature increases in core
 - Nuclear reactions start in shell around core
 - High temperature yields high luminosity
 - Star expands dramatically
 - Becomes a red giant

Fig. 21-3a, Red Giant Stage

3 Stages on Main Sequence

- Lower - stars less than 0.8 solar masses
 - Have lifetimes greater than age of galaxy
 - Have not evolved off main sequence
- Intermediate - stars between 0.8 and 8 solar masses
 - Evolve similar to sun
- Upper main sequence - stars more than 8 solar masses
 - have much different evolution
 - will treat them separately

Questions

- What happens after red-giant stage?
- If stars are mostly hydrogen and helium, what is origin of heavier elements from which earth is made?
- Does gravity win in the final stages of evolution?

Outline and concepts

- Evolution speeds up in later stages
- Mass loss occurs
- Will encounter new states of matter
 - White dwarfs
 - Neutron stars

- Also - new physics
 - Relativity
 - Black Holes
- Finally - explosions (supernovae)

Red Giant Stage

- Helium core keeps contracting, heating up, getting more dense
 - but doesn't produce nuclear energy
 - hydrogen fusion in shell around core produces the energy
- Eventually, core density so high that have to consider new state of matter

Degenerate matter

- Very high density, pressure
 - Ideal gas law no longer applies
- Matter so squeezed together
 - electrons lose complete freedom to move
 - Pauli exclusion principle sets limits
 - Pressure & temp. no longer directly related

Effects on star

- Star loses thermostatic control, which also kept it stable. In meantime,
 - core temp. keeps increasing
 - luminosity of star increases
 - star gets bigger
 - but core shrinks
 - eventually, core temp reaches 100 million deg

Helium flash

- At this temp, 3 He atoms can fuse to form 1 carbon atom (and produce energy)
 - core heats up
 - reaction accelerates, heats core even more
 - but pressure does not increase (degenerate matter)
 - runaway, potentially explosive situation
- Finally, core does expand, loses degeneracy
- outer layers of star shrink, become hotter
- star becomes a horizontal branch star
 - produces a carbon-oxygen core from the helium
- For the sun, its fate is sealed

Fig. 21-5, Stages in Stellar Evolution

Fig. 21-8, Evolution off the Main Sequence

Fig. 21-9 a, b, c, Evolution of a theoretical cluster

Fig. 21-d, e, f

How can we check these models?

- The different types of star clusters in the Milky Way provide the crucial tests

H-R Diagrams for Clusters

- Recall
 - Open Clusters
 - Globular Clusters
- Consider their H-R diagrams
 - See Fig. 21-9, 21-10
 - Note the different shapes
 - Note the different turn-off points for main sequences

Jewelbox Cluster H-R Diagrams for Pleiades, Prasepe

Fig. 21-11, H-R diagram of globular cluster
How age affects H-R diagrams for clusters
Fig. 21-12, H-R Diagrams of Open Clusters

- Main points
 - Difference in H-R diagrams is due to difference in ages
 - Main-sequence turn-off point indicates the age of the cluster
 - The lower the turn-off point on the main sequence, the older the cluster

Summary

- Cluster H-R diagrams provide a check of stellar evolution models
- Cluster H-R diagrams enable us to age-date clusters by the position of the main-sequence turn-off point