ASTR-1020: Astronomy II
Course Lecture Notes
Section II

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Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1020: Astronomy II at East Tennessee State University.

II. The Sun: An Introduction to Stellar Astrophysics

A. Overview of the Sun

1. The Sun is a 5 billion (5×10^9) year old <u>star</u>.

a) We know this by the fact that

i) The oldest rocks in the solar system (*e.g.*, Moon rocks and meteorites) are 4.6 billion years old as deduced by radioactive dating.

ii) The activity of the Sun's chromosphere and corona are consistent with a 5 billion year old one solar mass star.

iii) The energy output of the Sun (*i.e.*, luminosity and temperature) are consistent with interior models of a 5 billion year old, one solar mass, solar metalicity star.

b) It is our star, the stars we see at night are external to the solar system.

c) An object is not classified as a star unless it emits its own light via thermonuclear reactions inside the object.

2. We use the Sun as a *Rosetta Stone* — it helps us understand the structure of other stars.

3. The light we see from the Sun arises in the thin outer layers called the **solar atmosphere**. This atmosphere is divided into 3 layers:

a) **Photosphere**: White light sphere — the disk we see in the sky. It is the innermost layer of the atmosphere.

b) **Chromosphere**: The color sphere — seen as a red ring around the Moon during a solar eclipse. It is the middle layer of the solar atmosphere.

c) **Corona**: The crown — outermost layer of the atmosphere. It is the hottest layer (10^6 K) and can extend out to 2 solar radii ($R_\odot$).

4. Once a photon (particle of light) is emitted from the photosphere, it takes 8.5 minutes to pass the Earth's orbit — the Earth 8.5 light minutes from the Sun. (The Moon is 1.5 light seconds from the Earth.)

5. The Sun is a *main sequence* star (see §III of the notes) — a core hydrogen burner.

B. Interior Structure

1. The interior of the Sun is globally stable $\Longrightarrow$ it is in **hydrostatic equilibrium**, the weight of the star is balanced by the internal heat pressure pushing outward. The high internal pressure results from the high temperatures caused by the nuclear reactions in the core as shown by the **ideal gas law** where

$$P = N k_{\rm B} T \ , \qquad \text{(II-1)}$$

where P is pressure, N is the number density of particles that make up the gas, $k_{\rm B} = 1.38 \times 10^{-23}$ J/K, and T is temperature measured in Kelvin (*i.e.*, the absolute temperature scale).

2. Once energy (*i.e.*, photons) are created in the core of the Sun, they start to migrate outward (from hotter to cooler regions). It takes approximately 1 million years for these photons to escape the solar interior.

3. Heat energy can be transported by one of 3 mechanisms:

a) **Radiation transport**: Photon flow (*e.g.*, sunlight).

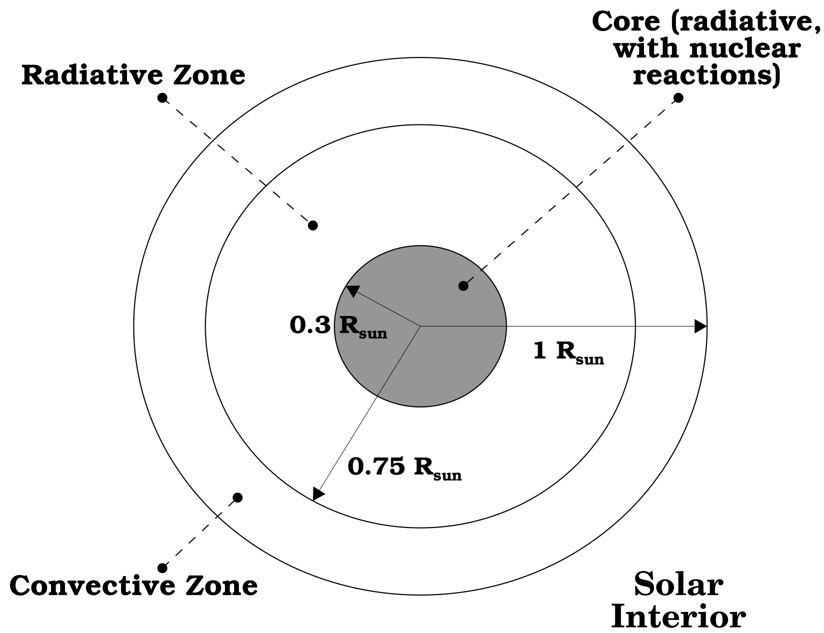
b) **Convection**: Blobs of hot gas rise from hotter regions to cooler regions (*e.g.*, boiling water).

c) **Conduction**: Atom and molecule collisions in a material (*e.g.*, an iron rod in a fire).

4. The energy transport mechanism that nature will use in a given situation is the one that is most efficient in transporting the energy.

5. In the Sun's interior, the core and much of its interior is radiative $\Longrightarrow$ energy flows via photons $\Longrightarrow$ **radiative zone**.

6. Convection is the most efficient means of energy transport in the outer layers of the interior $\Longrightarrow$ **convection zone**. We see the top of this zone in the photosphere as **granulation** (as discussed in Astronomy I).



C. Thermonuclear Reactions

1. The Sun's energy is produced by **thermonuclear reactions** in the core of the Sun.

a) Temperatures are high enough for 4 hydrogen (H) atoms to fuse into 1 helium (He) atom continuously at a very high rate.

b) The mass difference between 4 H atoms and 1 He atom is converted into energy via Einstein's famous equation $E = mc^2$, where E is the energy liberated, m is the mass difference, and c is the speed of light:

$$\begin{array}{rcl} \text{4 H atoms mass} & = & 6.693 \times 10^{-27}\ \text{kg} \\ \text{– 1 He atom mass} & = & -6.645 \times 10^{-27}\ \text{kg} \\ \hline \text{Mass Difference} & = & 0.048 \times 10^{-27}\ \text{kg} \end{array}$$

c) The Sun produces 9.0×10^{37} of these reactions per second releasing 3.9×10^{26} Joules of energy per second.

2. There are two different reaction chains that occur when hydrogen is being fused into helium: the **proton-proton chain**, which occurs in low mass stars like the Sun, and the **carbon-nitrogen-oxygen (CNO) cycle**, which occurs in high mass stars.

a) The proton-proton chain is as follows:

$^1\mathrm{H} + {}^1\mathrm{H}$	$\longrightarrow$	$^2\mathrm{H} + \mathrm{e}^+ + \nu$	(occurs twice)
$^1\mathrm{H} + {}^2\mathrm{H}$	$\longrightarrow$	$^3\mathrm{He} + \gamma$	(occurs twice)
$^3\mathrm{He} + {}^3\mathrm{He}$	$\longrightarrow$	$^4\mathrm{He} + {}^1\mathrm{H} + {}^1\mathrm{H}$	(for each time this occurs)

i) $^1\mathrm{H}$ = hydrogen atom (1 proton).

ii) $^2\mathrm{H}$ = heavy hydrogen (1 proton + 1 neutron)
= deuterium.

iii) $^3\mathrm{He}$ = light helium (2 protons + 1 neutron).

iv) $^4\mathrm{He}$ = helium (2 protons + 2 neutron)
= alpha particle (normal helium).

v) γ = gamma ray photon.

vi) e^+ = positron (positive charge)
= anti-electron (antimatter).

vii) ν = neutrino (neutral particle).

b) The CNO cycle:

$^{12}\mathrm{C} + {}^1\mathrm{H}$	$\longrightarrow$	$^{13}\mathrm{N} + \gamma$
$^{13}\mathrm{N}$	$\longrightarrow$	$^{13}\mathrm{C} + \mathrm{e}^+ + \nu$
$^{13}\mathrm{C} + {}^1\mathrm{H}$	$\longrightarrow$	$^{14}\mathrm{N} + \gamma$
$^{14}\mathrm{N} + {}^1\mathrm{H}$	$\longrightarrow$	$^{15}\mathrm{O} + \gamma$
$^{15}\mathrm{O}$	$\longrightarrow$	$^{15}\mathrm{N} + \mathrm{e}^+ + \nu$
$^{15}\mathrm{N} + {}^1\mathrm{H}$	$\longrightarrow$	$^{12}\mathrm{C} + {}^4\mathrm{He}$

- **i)** $^{12}\mathrm{C}$ = carbon-12 (6 protons + 6 neutrons) [most common form].
- **ii)** $^{13}\mathrm{C}$ = carbon-13 (6 protons + 7 neutrons).
- **iii)** $^{13}\mathrm{N}$ = nitrogen-13 (7 protons + 6 neutrons) [radioactive].
- **iv)** $^{14}\mathrm{N}$ = nitrogen-14 (7 protons + 7 neutrons) [most common form].
- **v)** $^{15}\mathrm{N}$ = nitrogen-15 (7 protons + 8 neutrons).
- **vi)** $^{15}\mathrm{O}$ = oxygen-15 (8 protons + 7 neutrons) [radioactive].
- **vii)** $^{16}\mathrm{O}$ = oxygen-16 (8 protons + 8 neutrons) [most common form].

3. The reactions described above all follow conservation laws:

- **a)** Mass-energy ($E = mc^2$) must be conserved.
- **b)** Lepton number must be conserved. Leptons are light particles: electrons, muons, tau particles and their respective neutrinos. Each lepton has an antilepton associated with it.
- **c)** Baryon number must be conserved. Baryons (see §X of these notes) are more massive particles composed of 3 quarks: protons and neutrons are baryons. Each baryon has an antibaryon associated with it.
- **d)** Charge must be conserved.

4. Interior modeling of the Sun does a remarkable job in reproducing the luminosity, temperature, and age of the Sun.

a) Oscillations that are seen on the Sun's surface tell us what is going on below $\Longrightarrow$ **helioseismology**. The structure that is deduced from these oscillations also agrees with the interior models.

b) In the 1960s observations of neutrinos coming from the Sun's core were first measured. The number of observed solar neutrinos is only 1/3 of what we expect to see $\Longrightarrow$ **solar neutrino problem**.

i) Quantum chromodynamics, which describes the physics of the nucleus, predicts that neutrinos should oscillate between the three different types of neutrinos that have been observed (*i.e.*, the electron neutrino, muon neutrino, and tau neutrino $\rightarrow$ the so-called neutrino *states*).

ii) Experiments at various neutrino detector facilities have recently shown that neutrinos do indeed oscillate between states as they travel, confirming the prediction from quantum chromodynamics and solving the solar neutrino problem.

5. The Sun is half-way through its "core hydrogen-burning" phase. We know this since one solar mass stars should last on the main sequence (see §III.C.) for 10 billion years and the Sun is currently 5 billion years old. As such, we have 5 billion more years before the Sun becomes a red giant, at which such time, it will "swallow" the most of the inner planets of the solar system.