

Lecture 13: Energy Generation & Transport in Stars

Readings: Section 18-2 and 18-3

Key Ideas

Energy generation in stars

- Nuclear Fusion in the core

- Hydrostatic thermostat

Getting the energy from the core to the surface

- 3 methods

Thermal Equilibrium in Stars

Putting Stars Together

Physics needed to describe stars

- Law of Gravity

- Equation of State (Ideal Gas Law)

- Principle of Hydrostatic Equilibrium

- Source of Energy (Nuclear Fusion)

- Way to transport energy to the surface

Energy Generation

- Stars shine because they are hot.

- To stay hot, stars must make up for the energy lost by shining

- Two energy sources available

 - Gravitational Contraction (Kelvin-Helmholtz)

 - Nuclear Fusion in the hot core

- Without a source of energy, a star would eventually cool off.

On the Main Sequence, stars are fusing H into He

- Proton-proton chain

 - Efficient at low Temperatures ($T_c < 18$ million K)

- CNO cycle

 - Efficient at high Temperatures ($T_c > 18$ million K)

Controlled Nuclear Fusion

Nuclear fusion is temperature sensitive. The rate of nuclear fusion depends on the temperature.

Higher Core Temperature=More Fusion

BUT

More fusion makes the core hotter,
Hotter core leads to even more fusion

Why don't stars explode like H-Bombs?

Hydrostatic Thermostat

If fusion reactions run too fast:

Core heats up, leading to higher pressure
Higher pressure makes the core expand
Expansion cools core, slowing fusion

If fusion reactions run too slow:

Core cools, leading to lower pressure
Lower pressure makes the core contract
Contraction heats core, increasing fusion

Thermal Equilibrium

Heat always flows from hotter regions into cooler regions.

In a star, heat must flow:

from the hot core, out through the cooler envelope, to the surface where it is radiated as light.

Energy Transport

There are three ways to transport energy

Radiation

Energy is carried by photons

Convection

Energy is carried by bulk motions of the gas

Conduction

Energy is carried by particle motions

Radiation

Photon leaves the core

Hits an electron or atom in about 1 cm and scatters

Slowly staggers to the surface in a “random walk”

Takes about 1 million years to reach the surface

Convection

Analogy is water boiling in a pot

Hot water is buoyant and rises against gravity

Displaces colder water down

Gives up its heat to the water at the top

Sets up a Convection Flow

Conduction

Heat is passed from atom-to-atom in a dense material from hot to cool regions

Analogy: Holding a spoon in a candle flame, the handle eventually gets hot.

Energy Transport in Stars

Normal Stars:

Mix of radiation and convection transports energy from the core to the surface

Conduction is inefficient (density too low)

White Dwarfs

Ultra-dense stars (10^5 g/cc)

Conduction dominates energy transport

Nearly uniform temperature throughout!

Radiation vs. Convection

Radiation carries the energy when
the opacity is low

the efficiency of energy transport can be low
Convection carries the energy when
the opacity is high
the efficiency of energy transport must be high

A Point about Luminosity

Luminosity of a star depend on two quantities:

The amount of internal energy

Energy=0 then Luminosity=0

The amount of energy transport

Transport=0 then Luminosity=0

The interplay between these can be quite interesting, as the energy transport can affect the energy generation and vice versa.

Structure along the Main Sequence

See Figure 20-11

Thermal Equilibrium in Stars

Thermal Equilibrium is when energy generation in the core is balanced by the transport of that energy to the surface

Energy Generation = star's Luminosity

Delicate balance

Make more energy than L, star expands

Make less energy than L, star contracts

Plays a vital role in the evolution of stars. At various points in the star's evolution, this happens.

Solar Model

Put all the Laws of Stellar Structure together and make a model of the Sun.

See Figure 18-4 and 18-5

How do we test?

Neutrinos

Helioseismology

Test: Helioseismology

We can test the composition of the sun by watching how sound waves go through it.

Result: He-rich core, the amount of He you would expect if the Sun had been fusing H to He for 5 billion years. We can also see the radiative core and the convective envelope and how temperature and density change throughout the Sun. Confirms our model of the Sun is correct.

Watch the Sun boil!

See Figure 18-10