Lecture 15: The Main Sequence

Readings: Box 21-2, Figure 20-11

Key Ideas

Main Sequence stars "burn" hydrogen into helium in their cores
  Get slowly brighter with age

The Main Sequence is a Mass Sequence
  Low M-S: $M < 1.2\ M_{Sun}$
  Upper M-S: $M > 1.2\ M_{Sun}$

The M-S lifetime depends on the Mass
  <u>Larger</u> Mass = <u>Shorter</u> Lifetime

Main Sequence Membership

To be a main sequence star:
  It must be in Hydrostatic Equilibrium (Pressure=Gravity)
  It must be in Thermal Equilibrium (Energy Generation=Luminosity)
  It must generate energy by "burning" H into He in its core

If any of these conditions is not met, the star is not on the main-sequence.
These conditions define a region on the H-R diagram where stars hang out for long periods of time. That's why so many stars in the sky (85%) are on the main sequence.

The Main Sequence is a Mass Sequence

The location of a star along the main sequence is determined by its mass.

  Low-mass stars: Cool & Low Luminosity
  High-mass stars: Hot & High Luminosity

Result of the Mass-Luminosity Relation:

$$L \propto M^4$$

Internal Structure

Nuclear reaction rates are very sensitive to core temperature

Proton-proton chain: fusion rate ~T^4

CNO cycle fusion rate~T^{18}!

Leads to

Difference in internal structure

Division into upper & lower M-S by mass

Dividing line is at ~1.2 M_{Sun}

Upper Main Sequence

$M > 1.2\ M_{Sun}$

$T_{core} > 18$ Million K

CNO Cycle fusion

<u>Structure</u>

Convective Core

Radiative Envelope

Lower Main Sequence

$M < 1.2 M_{Sun}$

$T_{core} < 18$ million K

P-P Chain

<u>Structure</u>

Radiative Core

Convective Envelope

The Lowest Mass Stars

$0.25 > M_{Sun} < 0.08\ M_{Sun}$

P-P Chain fusion

Fully Convective

Convective Core and Envelope

The Nuclear Timescale

The nuclear timescale is

$$\tau_{nuc} = f\varepsilon Mc^2 / L$$

f=fraction of nuclear fuel available for fusion (~10% in most cases)
ε= efficiency of matter-energy conversion (0.7% for hydrogen-helium fusion)
M=mass of star
L=luminosity of star

For the Sun:
    τ=10 Gyr

Stars=Cars? Part I

A low-mass star is like an economy car:
    Small fuel tank
    Low-power engine (low energy output)
    Excellent "gas mileage"
Consumes fuel very slowly
Result: Low-Mass stars stay on the Main Sequence for a very long time.

Stars=Cars? Part II

A high-mass star is like a Hummer
    Large fuel tank
    High power engine (high energy output)
    Low "gas mileage"
Consumes fuel very quickly
Result: High-Mass stars run out of fuel and leave the Main Sequence after a very short time.

Main-Sequence Lifetime

Nuclear Timescales:

$$\tau_{nuc} = f\varepsilon Mc^2 / L$$

Mass-Luminosity Relation:

$$L \propto M^4$$

Combine them

$$\tau_{ms} \propto \frac{1}{M^3}$$

Another way to think of this

$$\tau_{ms} = \frac{\text{constant}}{M^3}$$

(note this is a little different than the relation in Box 21-2. Use this relation)

Consequences:

High-Mass M-S stars have short M-S lifetimes

Low-Mass M-S stars have long M-S lifetimes

More massive main-sequence stars need higher pressures to support themselves against gravitational collapse. Higher pressure=higher temperatures. The higher temperatures lead to greater rates of nuclear fusion which means higher luminosity.

Example:

Low-mass Star (0.1 M_{Sun})

Question: what is the lowest mass star that has left the main sequence?

Consequences

If you see an O or B dwarf (=main sequence) star, it must be young as they die after only a few million years.

You can’t tell how old an M dwarf is because they live long and age slowly

The Sun is ~5 billion years old, so it will last only for ~5 billion years longer.
Start packing!

Brighter with Age….

Hydrostatic Equilibrium requires a high central pressure:

    Pressure=density x temperature

As H is fused into He, there are fewer nuclei:

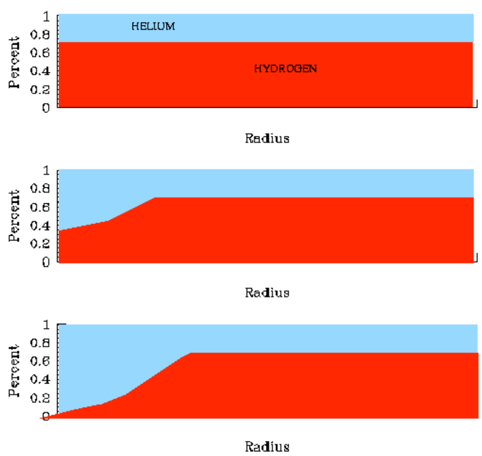
    Remaining nuclei must *move faster* to maintain the *same* pressure
    The gas gets *hotter*, so fusion runs *faster*

M-S stars get slowly brighter with age

    Small effect: ~1% brighter every 100 Myr years

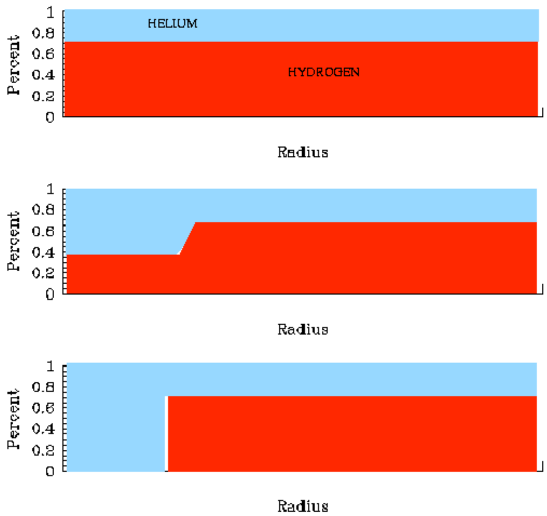
Compared to 4.5 billion years agao, the radius of the Sun ahs increased by 6% and the luminosity by 40%

Running out of Fuel—Low Mass



The star begins its life on the M-S with 70% H and 30% He.
Temperature is highest at the center, so nuclear reactions eat up H there faster.
H is gradually used up further and further away from the center.
It is a slow adjustment

Running out of Fuel – High Mass



Similar to low-mass stars, except convection brings new H from lower temperature regions. H is used up all throughout the core at a constant rate. When it is gone, it is all gone, so this leads to a rapid adjustment.