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: $M < 1.2 \, M_{\text{Sun}}$
   Upper M-S: $M > 1.2 \, M_{\text{Sun}}$

The M-S lifetime depends on the Mass
   Larger Mass = Shorter 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 $\sim T^4$
   CNO cycle fusion rate $\sim T^{18}$!

Leads to
   Difference in internal structure
   Division into upper & lower M-S by mass
   Dividing line is at $\sim 1.2 \, M_{\odot}$

Upper Main Sequence
M > 1.2 \, M_{\odot}
T_{\text{core}} > 18 \, \text{Million K}
CNO Cycle fusion
Structure
   Convective Core
   Radiative Envelope

Lower Main Sequence
M < 1.2M_{\odot}
T_{\text{core}} < 18 \, \text{million K}
P-P Chain
Structure
   Radiative Core
   Convective Envelope

The Lowest Mass Stars

0.25 > M_{\odot} < 0.08 \, M_{\odot}
P-P Chain fusion
Fully Convective
   Convective Core and Envelope

The Nuclear Timescale
The nuclear timescale is

\[ \tau_{\text{nuc}} = \frac{f \varepsilon M c^2}{L} \]

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

For the Sun:
\[ \tau = 10 \text{ Gyr} \]

**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:**
\[ \tau_{\text{nuc}} = \frac{f \varepsilon M c^2}{L} \]

**Mass-Luminosity Relation:**
\[ L \propto M^4 \]
Combine them

\[ \tau_{\text{ms}} \propto \frac{1}{M^3} \]

Another way to think of this

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

(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 \( M_{\text{Sun}} \))

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 \times \text{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 ago, the radius of the Sun has 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.