Today

- Recall that C-N-O cycle in massive stars yields (very) short lifetimes on main sequence (MS)
- Test ideas of lifetimes by seeing peel-off from MS as evident in star clusters
- Discuss how a star may be born: getting to the MS
- Homework # 5 due today, new HW # 6 passed out
- Finish detailed reading of Chap 16: Star Birth
- Class meets in Fiske Planetarium this Thursday – go there directly: Birth of Stars with Ben Brown
- Term project on Extra-Solar Planets using Planet Finder will be distributed and discussed on Friday

When does a star leave the main sequence?

E.

- A. After a few million years
- B. After a few billion years
- C. It depends on its mass
- D. When the hydrogen fuel in its core is used up
- E. C and D

REMINDER

C-N-O Cycle

- Can provide vast luminosity for massive stars on MS
- “Observed” MASS – LUMINOSITY relation on MS
- BIGGER CRUSH OF GRAVITY needs
  - HIGHER central PRESSURE (or temperature)
  - FASTER BURNING (CNO-fusion-cycle comes into play)

REMINDER

"Observed" MASS – LUMINOSITY relation on MS

L ~ M^4
Thus we get this huge range of lifetimes on MS. Higher on MS, higher mass, shorter lifetime.

**How MS stars do it**

**1. Hydrostatic Equilibrium:**
   - Convective core and radiative zone
   - New balance to produce energy

**2. Energy Transport:**
   - By radiation in massive stars
   - By convection in low-mass stars
   - Mass ≈ 1.5 M☉: Radiation core, radiative envelope
   - Mass > 2 M☉: Convection core, radiative envelope

**3. Nucleosynthesis Generation:**
   - Mass ≤ 8 M☉: \( ^{2} \text{He} \) in core
   - \( M > 8 \text{M☉} \):
     - \( ^{3} \text{He} \) in core
     - \( ^{3} \text{He} \) in core
     - \( ^{3} \text{He} \) in core
     - \( ^{3} \text{He} \) in core

**Sizes of stars main sequence**

**Differing convection and radiation zones on MS**

- **High mass:** convective core, deep radiative envelope
- **Solar mass:** radiative interior, convective envelope
- **Low mass:** very deep convective envelope

Deeper convection may yield fiercer magnetic dynamos

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**Crib Sheet Awards Ceremony**

- **Three categories this time:**
  - Most Aesthetic Appeal
  - Most Economical Use of Space
  - Finest Colorful Scribing

This award goes to the crib sheet with the best artistic presentation.

**Is presented to:**

Kathryn Grasha
This award, for the crib sheet with
The Most Economical Use of Space
presented to
Garston Tremblay

This award, for the crib sheet with
The Most Colorful Scribing
presented to
Sarah Hampton

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**Reading Clicker -- life tracks**

- What can we find out about a star from its life track on the H-R diagram?

  **B.**

  - A. When the star was born
  - B. The surface temperature and luminosity of the star at each stage of its life
  - C. The star’s current stage of life
  - D. Where the star is located

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**Clicker -- Stellar Evolution**

- Which is correct order for some stages of life in a low-mass star?

  **A.**

  - A. protostar, main-sequence star, red giant, planetary nebula, white dwarf
  - B. protostar, main-sequence star, red giant, supernova, neutron star
  - C. main-sequence star, white dwarf, red giant, planetary nebula, protostar
  - D. protostar, main-sequence star, planetary nebula, red giant

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**STAR CLUSTERS -- two varieties**

both are groups of star that have evolved together --
great for testing ideas about evolution of stars

- Globular cluster
  - old, millions of stars
- Open cluster
  - young, thousands of stars

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Law AFTER main sequence

Stars evolve
off MS, not along it!

Now let us test such ideas with star clusters
Discussion Topic

What do we learn about stellar evolution by studying “Cities of Stars” (big star clusters)

Why use a globular cluster, and not just a vast bunch of field stars?

Globular clusters -- much older, bigger

- generally much older -- up to 13 BILLION years
- made up of millions of stars, very densely packed

Open star cluster: Pleiades

- “Open cluster” only about 100 MY old -- involves several thousand stars
- Unlike Sun’s age of 4.6 BY

Bright B-type stars, O stars now missing

Clusters can test lifetimes on main sequence

Great advantages:
- All stars at about same distance (apparent brightness tracks luminosity)
- All formed at about same time
- Range of different mass stars!
- Stars “peel off” MS as core H exhausted \(\rightarrow\) red giants

Life track in H-R diagram of solar-mass star

Many meanders, but MS phase longest, red giant phase(s) shorter, finally white dwarf left to cool slowly

Post-MS Evolution

- Read Chap 17: “Star Stuff” carefully about life-tracks for both low-mass and high-mass stars after the main sequence
- We will discuss these next week
- Now we look at how stars arrive at the MS, looking at elements of star birth
- Next class meets directly in planetarium for our custom “Birth of Stars” presentation
Our Milky Way Galaxy

- 100-400 billion stars
- 100,000 light years in diameter, or ~30,000 pc = 30 kpc (kilo-parsecs)
- Sun is located about 8.5 kpc from center, in the ‘Orion Arm’

Artist’s sketch!

Milky Way Anatomy: Spiral Galaxy

- **Disk**: includes spiral arms -- young, new star formation
- **Bulge & Halo**: older stars, globular clusters

If we might see Milky Way from outside

Spiral Sb galaxy NGC 4414

Grand design spiral” – M51 Whirlpool

Disk stars/gas rotate through “traffic jams”

Bright O & B stars mark the spiral pattern: regions of star birth

“Traffic jam” in the disk

Disk is very thin!

Disk is very thin!

Artist’s edge-on view

The Star-Gas-Star Cycle

BIG disk recycling:
Cycle of stars $\rightarrow$ gas $\rightarrow$ stars
**Inventory of “stuff” making up our galaxy**

- **Stars**: Few million billion, $\geq 10^{11}$
- **Gas**
  - Very cold gas: star birth
  - Cool gas: neutral H
  - Hot H
- **Dust**: Very fine particles
- **“dark matter”**

**Ingredients of Interstellar Medium (ISM)** (stuff between the stars)

1. **Stars**
2. **Gas**: 10% mass of stars
   - Very cold gas in H II regions
   - Cool gas in ISM regions
   - Hot gas
3. **Dust**: 1% mass of stars

**Beauty and richness of the ISM**

- Emission nebulae around star birth regions
- Interstellar medium (ISM)

**Gravitational collapse of “molecular clouds”**

- Battle between (1) gravity pulling inwards building clumps, (2) pressure of heated gas pushing outwards to resist further collapse → Need big clouds & cooling

**Simulation of giant cloud collapse and birth of stars**

**Stages in building the PROTOSTAR**

1. Surface temperature rise when radiation breaks the hydrogen bond to form the protostar
2. The protostar shines brightly as gravitational/potential energy is converted into thermal energy
3. The fusion core increases until the mass of the star is high enough to sustain the fusion
4. The fusion core increases until the mass of the star reaches a critical point
Too much angular momentum – jet it away!

Many jets from young stellar objects

Actual edge-on disk and jet (Hubble ST)

Often protostar is still hidden in cocoon of dust – and jets are episodic (Herbig-Haro objects)

More massive protostars get to MS faster!

Collapse of molecular cloud makes many small stars, fewer massive O & B stars