Astro 210
Lecture 31
April 9, 2018

Announcements:

- **HW9 due online in PDF, Friday 5:00 pm**

- **Solar Observing raindates this week** April 9–14
  Mon, Tue, Wed, Thurs. 11:15 am to 2:45 pm
  Campus Observatory
  allow 20-30 minutes. take **selfie** with telescope

- Grading: I apologize for slowness–lots of new results this week

The Story Thus Far

color: measure by *ratio* of flux at different λ

$\leftrightarrow$ *differences* of magnitudes in different passbands

Q: how does color depend on star distance?

Q: what does color tell about star?

Hertzsprung-Russell Diagram

- *Q: what's that? What's plotted?*
- *Q: main features?* **be able to sketch!**
- *Q: what do we learn about the Sun?*

mass: *Q: how measured?*

Hertzsprung-Russell Diagram

plots star L vs T (theorist-friendly)
or *absolute magnitude vs color* (observer-friendly)
hence also known as *color-magnitude diagram = CMD*

for a "fair sample" of stars (i.e., not a specially picked cluster)
trends emerge:

⋆ *most* stars ($\sim 90\%$) fall on curve: **main sequence**
(including the Sun!); *"dwarfs"*
⋆ most of the rest: cooler but more luminous: **giants**
⋆ a rare few: hot but luminous: **supergiants**
⋆ not rare but dim and hard to find:
very hot but very low-L objects: **white dwarfs**

the Sun:
- a Main Sequence star
- typical in temperature, luminosity – a Copernican result!

iClicker Poll: Stellar Luminosity and Mass

Vote your conscience!

How are a star's luminosity and mass related?

A directly: larger $M \longrightarrow$ larger L

B inversely: larger $M \longrightarrow$ smaller L

C no strong dependence: L nearly constant for all M

for many stars find M, L $\rightarrow$ plot!

`www:` M `vs` L `-- beware!  logarithmic axes`

for *main sequence* stars ("normal" stars)
there is a simple, clear correlation

mass-luminosity relation (main sequence):

$$L \propto M^4 \tag{1}$$

where M is now mass, not magnitude!

Note: this is a rough approximation, not accurate for $M \gtrsim 4 M_{\odot}$

Q: what is L of $0.5 M_{\odot}$ star?

Q: what does this mean for main sequence on HR diagram?

The Facts of Life for Stars: Revisited

Fact: stars constantly radiates energy
and at a huge rate!
for the Sun: $dE/dt = L_\odot = 4 \times 10^{26}$ Watts!

Fact: stars have a finite ($\neq \infty$) mass
and thus a finite fuel supply (whatever that fuel may be)

Fact: Energy is conserved
no free lunch!

Q: therefore?
Q: some stars are alive today, so...?

Stars and Energy Conservation

we have shown:
energy conservation demands that **stars must die**

that is, stars have finite lifetimes

but some stars are alive today
$\longrightarrow$ cannot have been around forever
ergo: **stars must be born**

stars have life cycles!

iClicker Poll: Stellar Lifetime

Stars of which mass live longer–$1M_\odot$ or $0.5M_\odot$?

A $1M_\odot$: higher M $\longrightarrow$ more fuel

B $0.5M_\odot$: lower L $\longrightarrow$ longer to "burn out"

C effects cancel: lifetimes roughly equal

∞

Stellar Lifespans

From M and L get *lifespan* τ
since energy conservation gives

$$\begin{array}{rccc} E = & L & \times & \tau \\ \text{energy supply (fuel)} = & \text{burn rate} & \times & \text{lifespan} \end{array} \tag{2}$$

thus: $\tau = E/L$

but $E \propto M$: hydrogen mass is thermonuclear fuel

- $\tau = E/L \propto M/M^4 = M^{-3}$
- using solar values $\tau_\odot = \tau(M_\odot) = 10^{10}$ yr, get

$$\tau = 10^{10} \text{ yr} \left(\frac{1 M_\odot}{M}\right)^3 \tag{3}$$

- high mass $\leftrightarrow$ high luminosity $\leftrightarrow$ short life
- low mass $\leftrightarrow$ low luminosity $\leftrightarrow$ long life

Stellar Lifetimes: Implications

Some Facts:

- main sequence mass-lifetime relation:

$$\tau = 10 \text{ billion yr} \left(\frac{1 M_\odot}{M} \right)^3 \tag{4}$$

- age of Sun and solar system: $t_{SS} = 4.5$ billion yr
- age of the Universe (we'll find): $t_0 = 13.7$ billion yr

Q: what's the lifespan of a $0.5 M_\odot$ *star? implications?*
Q: what's the lifespan of a $10 M_\odot$ *star? implications?*
Q: implications for main sequence on HR diagram?

Imagine (for simplicity) that:

- our Galaxy has formed stars at a constant rate throughout the age of the Universe (oversimplified!)

Q: what would this mean for the population of Galactic stars today?

Stellar Lifetimes: Implications

Implications:

- $\tau(0.5M_\odot) = 80$ billion years $\gg$ age of Universe!
  $\longrightarrow$ all such stars ever born remain alive today!
- $\tau(10M_\odot) = 10$ million years $\ll$ age of U., SS
  $\longrightarrow$ most such stars have come and gone!
  $\longrightarrow$ any massive stars seen today were recently born

So as our Galaxy makes stars

- *low-mass stars live "forever"* (but are dim)
- *high-mass stars die quickly*

$\longrightarrow$ expect mostly low masses (in a fair sample)
but beware bias – rare, luminous stars easier to see
example of "selection effect"

`www: HR diagram: nearest vs brightest stars`

Theory Building: Stellar Life Cycles

Other questions arise:

- *why* do most stars lie on the main sequence?
- what controls their position on the diagram?
- what's up with the giants, supergiants, and white dwarfs?

to understand these, need *theory* of stars

Q: what is involved in making a model of a star's life?

for example, consider a model of the Sun's life

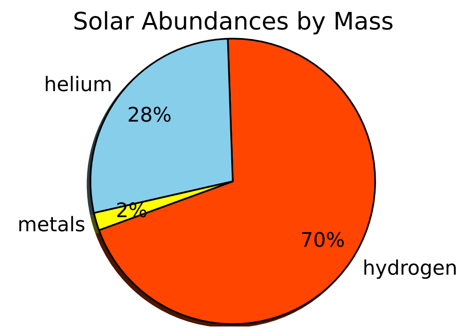
Q: what physics goes in?

Q: what data needed as inputs and/or checks on model outputs?

Q: what kind of predictions can such a solar model make?

The Life and Death of a $1 M_\odot$ Star

Evolution of a $1 M_\odot$ Star: Birth



Protostar in cold molecular cloud
composition: H and He in gas form, and
other=heavy elements="metals" mostly in dust
`www: Eagle Nebula`

initial collapse: 'free fall' (HW 7)
most material $\rightarrow$ protostar
nonzero angular momentum $\rightarrow$ protoplanetary disk
(see solar system origin notes; magnetic fields become important too)

protostar contraction: *gravitational potential energy $\rightarrow$ heat*
Q: when does contraction end? when is it hot "enough"?

From Protostar to Main Sequence

- core T until hot enough for
  nuclear reactions to turn on

Once H→He "burning" starts: heat supply!
- gas pressure maintained
- hydrostatic equilibrium achieved → star stabilized

begins main sequence phase

Q: how to test this?

Hint: want to isolate a group of young stars
Q: how to do that?

Star Clusters as Stellar Laboratories

molecular clouds are stellar nurseries
each generally gives birth to many stars
$\longrightarrow$ *most stars born in clusters*

$\star$ most star clusters not gravitationally bound
i.e., member star speeds $>$ cluster escape speed
$\longrightarrow$ most clusters “dissolve” or “evaporate” quickly

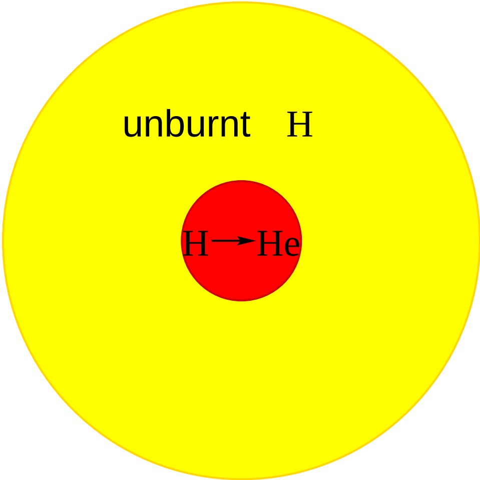
before stars are scattered, observe as: **open cluster**
`www: open cluster examples`
irregular shapes, often some remains of natal gas/dust cloud

open clusters short lived $\longrightarrow$ *made of young stars*

Q: HR diagram for open cluster–prediction?

$1M_\odot$ Star Mid-Life: "Main Sequence"

main sequence = nuclear reactions "burn" H $\longrightarrow$ He in core

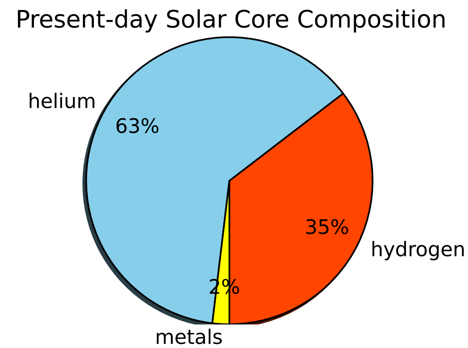


most stars are found on main sequence
$\longrightarrow$ *most of a star's lifespan spent in this phase*

Q: how does star core change in composition during this time?

Q: how will the Sun respond to this change?

Evolution of the Sun's Luminosity



in star core: H $\rightarrow$ He "burning"

$\rightarrow$ over time: H "fuel" $\rightarrow$ He "ash"

$\rightarrow$ fuel supply goes down

e.g., today, Sun's core $< 50\%$ H!

how does core respond to H depletion?

- $4p + 2e \rightarrow {}^4$He means *fewer but heavier particles*
- but must maintain pressure support against gravity
- $PV = N_{\text{particles}} kT$: with less fuel, have to burn hotter

$\rightarrow$ *core T goes up*

$\rightarrow$ star responds by *increasing L!*

Q: how would this "move" the Sun on the HR diagram?

Today: sun $\sim 50\%$ brighter than at birth!