Astro 404
Lecture 7
Sept. 11, 2019

Announcements:

- **Problem Set 2 posted, due Friday**
  Note in Q2(c) "explain how we can measure ... r_1, r_2, and P"
  means: say *which measurements* needed,
  and explain *how to use them* to deduce these quantities

- Office Hours: Instructor–right after class today
  TA tomorrow noon-1pm

- Lecture notes sometimes updated soon after class
  and sometimes include "Director's Cut Extras"

Last Time

binary stars as laboratories for stellar masses

Q: how common are binaries?

Q: classifications of observed binaries? `www: examples`

Q: in eclipsing binaries–why 2 eclipses? what sets period?
Q: what sets eclipse eclipse depths? widths?

Binary Stars–Now You Know

observed binary separations (semi-major axes) span huge range
from nearly touching (!) to $> 10^4$ au (e.g., Proxima Cen)
if close enough, binary can dramatically affect system evolution!
we will return to this after studying single stars

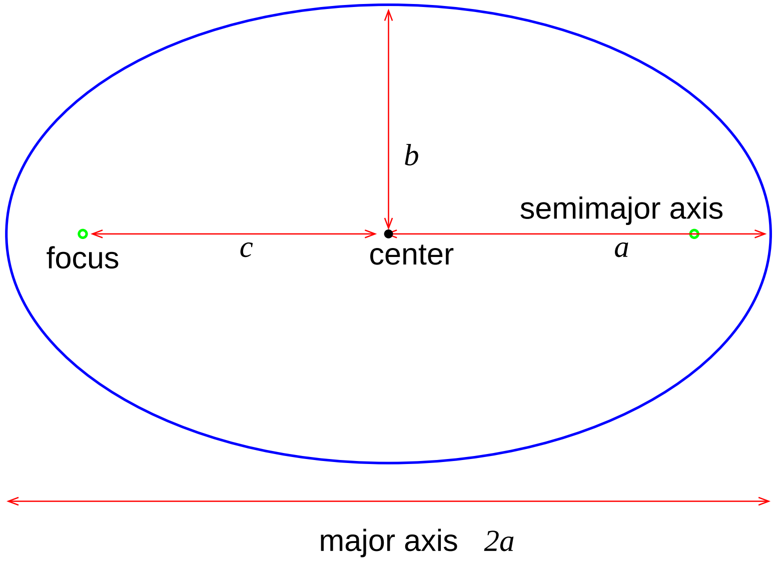
ASTR 405 alumni:
you'll note *binary star physics and techniques*
very similar to methods used in *exoplanet* research

- but exoplanets are harder to find!
- historically, binary star studies came first
  techniques carried over to exoplanets

Q: dynamics of binaries?

Newtonian Orbits: Kepler's Laws

orbits of gravitationally bound spheres



I. *in space:*
orbits are ellipses
with *center of mass at one focus*

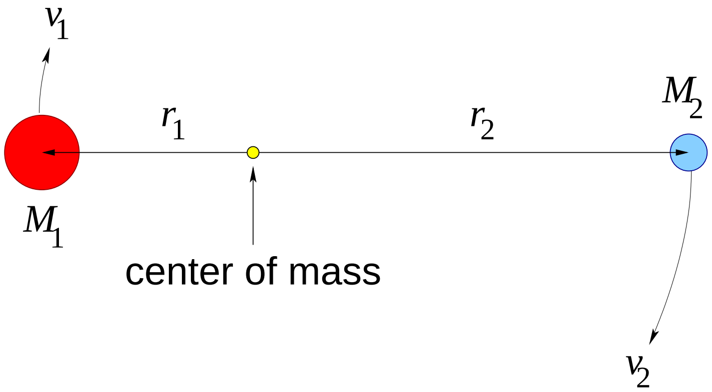
II. *speed:* **orbits sweep equal areas in equal time**

III. *period and size related:*

$$4\pi^2 a^3 = G(m_1 + m_2)P^2 \tag{1}$$

Q: how does the circular case fit in?
Q: equal mass particle motions about COM? unequal masses?

Motion About Center of Mass



COM positions: $r_1/r_2 = m_2/m_1$ (PS2)
star separation: $r = r_1 + r_2$

measure P, and r_1, r_2
→ find mass ratio

problem (PS2): must measure r's
Q: how to do this for visual binaries? spectroscopic?

iClicker Poll: Star Masses

Vote your conscience!

Measure *mass* M and and *luminosity* L for main sequence stars
plot L vs M; each star is one (M, L) point
What trend(s) will we find?

A M and L tightly related: L increases with M
(more massive = more luminous)

B M and L tightly related: L decreases with M
(more massive = less luminous)

C M and L unrelated: large spread in L for each M

D none of the above

`www: observational data`

Star Masses

For *main sequence stars*
data show very tight trend
for masses near $1 M_\odot$, good approximation is
$\log L = \nu \log M + const$, with $\nu \approx 3.5$ for masses near $1 M_\odot$
$\rightarrow$ solve to find $L \propto M^\nu$, and use $L(M_\odot) = L_\odot$:

$$L = \left(\frac{M}{M_\odot}\right)^{\nu} L_\odot \approx \left(\frac{M}{M_\odot}\right)^{3.5} L_\odot \tag{2}$$

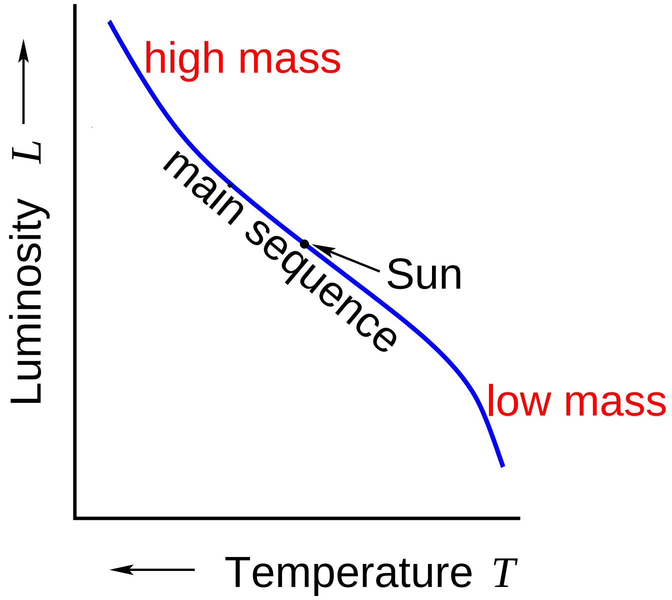
very strong increase of L with M!
example: $L(2 M_\odot) = 2^{3.5} L_\odot = 11 L_\odot$

Q: which has more total lum?
2 stars at $1 M_\odot$, or 1 at $2 M_\odot$?

Q: what does this mean for the H-R diagram?

Decoding the H-R Diagram: Main Sequence and Mass

in the H-R diagram
the main sequence is a
tight correlation or
one-to-one relationship
between T and L



mass measurements further show
mass-luminosity correlation

the Main Sequence is really a sequence in mass!

on Main Sequence:

- low mass ↔ low T ↔ low L
- high mass ↔ high T ↔ high L
- observed masses roughly span $(0.1 M_\odot, 100 M_\odot)$
- *Q: consequences of large range in* L*?*

Stellar Energy

main sequence luminosities span roughly $(10^{-4} L_{\odot}, 10^{4} L_{\odot})$
huge range in power output

but energy conservation requires luminosity power to be generated by a "fuel" of some kind

$$\left(\frac{dE}{dt}\right)_{\mathrm{emitted}} = L = \left(\frac{dE}{dt}\right)_{\mathrm{fuel}} \tag{3}$$

so *total energy requirement* for fuel
over a star's main sequence lifespan τ is

$$E_{\mathrm{fuel}} = \int_0^{\tau} L \; dt \approx L \; \tau \tag{4}$$

Q: should available fuel depend on star mass? how?
Q: implications for lifespan?

Main Sequence Lifespans and Mass

it stands near to reason (and turns out to be right)
that *more mass* ↔ *more available fuel*

simplest such relation (also turns out right): linear proportionality

$$E_{\text{fuel}} \propto M \tag{5}$$

and since we have $E_{\text{fuel}} \approx L \; tau$
predict *main sequence lifespan* depends on mass:

$$\tau(M) \approx \frac{E_{\text{fuel}}(M)}{L(M)} \sim M^{1-\nu} \tag{6}$$

so for masses near $1 M_\odot$: $\tau \sim M^{-2.5}$
Q: how can this be? doesn't more mass mean more fuel?

Q: implications for HR diagram?
Q: how can we test this?

Prediction: MS Lifespan Depends Strongly on Mass

main sequence lifespan: expect $\tau \sim M^{-\nu} \sim M^{-2.5}$

- strong dependence on mass!
- *high mass* ↔ *short lifespan*
- *low mass* ↔ *long lifespan*

to test:

- *find clusters of stars that were born together*
- plot on HR diagram, and compare main sequences
- prediction: young clusters → entire MS populated
  old clusters → no upper MS (high L, T), but full lower MS

Q: analogy in mosquito/human fable?

How to tell old vs young clusters?

`www: open clusters` versus `www: globular clusters`

consider *shape* ("morphology") and *environment*

Q: which is likely old? which young?

Star Clusters and Ages

globular clusters

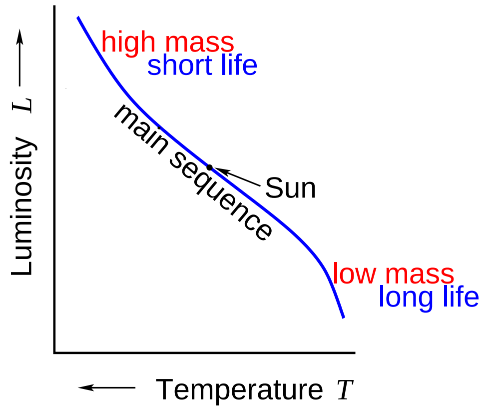
stars tightly packed in sphere
→ suggests equilibrium
isolated from other stars and gas (out of Galactic plane)
→ no raw materials, unrelated to ongoing star formation

open clusters

stars loosely grouped, with irregular shapes
→ suggests disequilibrium (not round!)
often near gas and dust clouds and many other stars
→ raw stellar materials and active star formation nearby

best available data is hot off presses: *Gaia!*
`www: Gaia results`
Q: trends in MS? giants? white dwarfs?

Star Cluster H-R Diagrams: Evolution Revealed!



our predictions confirmed!

- *young open clusters* have *full MS*
- *old globular clusters* have lower MS but *no stars with above* $\sim 1 M_\odot$

more clues:

- some open clusters have no giant branch!
- other open clusters lack highest masses, and have some (super)giants
- open clusters have very few white dwarfs
- globular clusters have no supergiants but full giant branch

Q: what does this suggest?

(Super)Giant Phase Follows Main Sequence

giant branch and white dwarf sequence emerge as clusters age at expense of ever more of upper main sequence

implications: *this is due to stellar evolution!*

- *highest mass stars quickly evolve from MS to supergiants*
- lower masses progressively evolve from MS to giants
- globular cluster MS "turnoff" near $1 M_\odot$ suggests stars with $M \lesssim 1 M_\odot$ live a very long time!
- white dwarfs also arise after MS

Decoding the H-R Diagram: Evolution Revealed!

main sequence is *ordered by mass*
and star properties do not change much during MS phase
in particular: a star does not move up or down the MS
Q: why not? what would that mean for clusters?

giants and supergiants are phase after MS
most massive MS stars → supergiants
then, ever more slowly, MS → giants
until very long MS lifespans at $M \lesssim 1 M_{\odot}$

and thus **stellar evolution is stellar transformation**

- ▷ *stars change color, temperature, luminosity, and size over time*
- ▷ these changes are modest and slow during main sequence
  but dramatic and increasingly rapid after MS ends

The Mighty H-R Diagram

note the power of the HR diagram
and the progress we have made
still with very basic physics only

and the HR diagram has more information
which we will uncover in weeks to come

many question remain: how do stars arrive on the MS?
how and why do stars linger on the MS?
why do stars become giants? how do they leave this phase?
what is role of white dwarfs?

to make further progress – *need to develop theory of stars*