ASTRO 310: Galactic & Extragalactic Astronomy
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The Milky Way Galaxy: Stars in the Solar Neighborhood
What stars are we seeing in an optical image of a galaxy?

Milky Way

M104
Sombrero Galaxy
Which stars contribute the most light in these galaxy images?

A  stars like sun
B  stars more luminous than the sun
C  stars less luminous than the sun
D  stars more massive than the sun
E  stars less massive than the sun
Which stars contribute the most light in these galaxy images?

A  stars like sun
B  stars more luminous than the sun
C  stars less luminous than the sun
D  stars more massive than the sun
E  stars less massive than the sun
we need a census of stars (somewhere…) to help us interpret the starlight we detect from galaxies
Milky way: edge-on schematic view

- "solar neighborhood", $d<100$ pc, only small part of disk

solar neighborhood is pretty tiny region compared to whole galaxy
Milky way: edge-on schematic view

- “solar neighborhood”, d<100 pc, only small part of disk

The solar neighborhood is a pretty tiny region compared to the whole galaxy, with a volume that is ~1 millionth of the entire galaxy (within the radius of the sun).
HR diagram of stars in Solar Neighborhood

main sequence is a mass sequence

$L = 4\pi R^2 \sigma_{SB} T^4$ for stars

giants have larger radius for same $T$

how to get $L$: measure flux (or brightness), figure out distance --> get $L$ from $L = 4\pi D^2 f$
in order to know what stars are making the most light from galaxies, need to know both L-T diagram and how many stars of each type there are
Most light from galaxies comes from a small number of very luminous stars.
Most (stellar) mass is in a large number of faint stars, which are not directly detected.

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<th>MASS $\mathcal{M}_\Phi$</th>
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luminosity function $\phi(L)$ or $\phi(M)$

what is the relative number of stars with different luminosities?

$\phi(L)$ how many stars of each luminosity $L$ (or absolute magnitude $M$) exist in each pc$^3$

$\phi(L)$ has units of $\frac{\# \text{ stars}}{(\text{luminosity interval}) (\text{volume})}$
in order to make HR diagram (L-T diagram) or luminosity function, need to know distances to stars!

how do we measure distances to stars?
Hipparcos satellite mission
1989-2000

Measured positions and motions of ~2 million stars in Milky Way, including parallax motions to learn distances
Measuring Distances to Nearest Stars with Stellar Parallax

Stellar parallax: apparent motion of nearby stars against background of more distant stars and galaxies

causd by earth’s orbital motion around sun
Stellar parallax: apparent motion of nearby stars against background of more distant stars & galaxies

Caused by earth’s orbital motion around sun

\[ d(\text{parsecs}) = \frac{1}{p(\text{arcseconds})} \]
Parallax in different directions

In earth’s orbital plane, parallax motion traces out lines. Perpendicular to earth’s orbital plane, parallax motion traces out circles. In other directions, parallax motion traces out ellipses.
Parallax effect exaggerated by 100,000x
now that we have distances, we can learn the luminosities of stars, and make an HR diagram
HR diagram of stars in Solar Neighborhood

how to get L: measure flux (or brightness), figure out distance --> get L from $L = 4\pi D^2 f$

$L = 4\pi R^2 \sigma_{SB} T^4$ for stars

giants have larger radius for same $T$
L and T are related since stars are well approximated by spherical blackbodies

Luminosity = Area × Flux

\[ L = A \cdot F \]

Area = \(4\pi R^2\) for sphere

Flux = \(\sigma_{SB} T^4\) for “blackbody” source

\[ L = 4\pi R^2 \sigma_{SB} T^4 \] for stars

at a given T in the HR diagram, MS stars all have the same luminosity since they have the same radius R

at the same T, giant stars all have a greater luminosity since they have a much greater radius R

L luminosity: rate of energy output (in form of EM radiation) in all directions, integrated over all wavelengths (erg s\(^{-1}\))
HR diagram of stars in Solar Neighborhood

Surface temperature

- 30,000 K
- 6000 K
- 3000 K

Sun

Main sequence is a mass sequence

30 $M_{\text{sun}}$

Giant

1 $M_{\text{sun}}$

0.1 $M_{\text{sun}}$

Absolute magnitude $M_{\text{Hp}}$

Luminosity ($L_{\odot}$)

Color B-V (magnitudes)
• *Initial mass* is the most important fundamental property of a star, since it determines *the entire life history of a star*

• Initial mass (largely) determines:
  - L, T, color, size, lifetime

• *Main sequence* of HR diagram is *mass sequence*

*(Initial elemental composition is 2nd most important property)*
How do you determine masses of stars? based on binaries ... and Newton’s (or Kepler’s) laws
measure orbital period $P$
measure separation $a$ (need to know distance)
→ get masses from Newton’s (Kepler’s) laws

\[ P^2 = \frac{a^3}{(M_1 + M_2)} \]

$P$ in years
$a =$ mean separation in A.U.
$M_1$ and $M_2 =$ star masses in solar masses
this gives you the sum of the masses!
… but how do you get individual masses?
Determining stellar masses in binaries

\[ r = r_A + r_B \]

\[ M = m_A + m_B \]

\[ m_A r_A = m_B r_B \]

true at any time in orbit true for any \( r_B, r_A \)
Determining stellar masses in binaries

measure orbital period $P$
measure separation $a$
(need to know distance)
→ get sum of masses from Kepler’s 3$^{rd}$ law
(comes from Newton’s Laws of Motion & Gravity)

$$P^2 = \frac{a^3}{(m_A + m_B)}$$

$P$ in years
$a =$ mean separation in A.U.

star masses in solar masses

get individual masses from $m_A r_A = m_B r_B$ relation
**Mass-Luminosity Relation** for main sequence stars

*Determined from Binary Stars*

Approximate form:

\[
\frac{L}{L_{\text{Sun}}} \approx \left( \frac{M}{M_{\text{Sun}}} \right)^3
\]

The mass-luminosity relation is highly non-linear:

- Increase mass by 10x
- Increase luminosity by \( \sim 1000x \) !!

More accurate form:

- If \( M \geq 0.43 \; M_{\text{Sun}} \) then,
  \[
  \frac{L}{L_{\text{Sun}}} = \left( \frac{M}{M_{\text{Sun}}} \right)^{4.0}
  \]

- If \( M \leq 0.43 \; M_{\text{Sun}} \) then,
  \[
  \frac{L}{L_{\text{Sun}}} = 0.23 \left( \frac{M}{M_{\text{Sun}}} \right)^{2.3}
  \]
luminosity-mass relation for main sequence stars:

\[ \frac{L}{L_{Sun}} \approx \left( \frac{M}{M_{Sun}} \right)^3 \]

Q: why does L depend so strongly on M?

main sequence lifetime-mass relation:

\[ \frac{t_{MS}}{t_{sun}} \approx \left( \frac{M}{M_{Sun}} \right)^{-2.5} \]

Q: why does t_{MS} depend so strongly on M?
the main sequence lifetime of a star at the “turn-off” point of the main sequence is equal to the age of the star cluster
HR diagram of nearby stars

HR diagram of globular cluster

Lum <- Temp

<- Temp
HR diagram of nearby stars

HR diagram of globular cluster

Range of ages

All the same age (& old)
how do we learn the relative numbers of stars at each L?

how do we come up with a good census of stars in some fixed volume near the sun?
observe all sources brighter than some minimum flux: number of sources observed vs L in flux-limited survey

number observed in flux-limited survey $N(L)$
luminosity function $\phi(L)$ or $\phi(M)$
what is the relative number of stars with different luminosities?

$\phi(L)$ how many stars of each luminosity $L$ (or absolute magnitude $M$) exist in each pc$^3$

$\phi(L)$ has units of

$$\frac{\text{# stars}}{(\text{luminosity interval}) (\text{volume})}$$
luminosity function $\phi(L)$ or $\phi(M)$

what is the relative number of stars with different luminosities?

$\phi(M_V)$ how many stars of each absolute magnitude $M_V$ (or luminosity) exist in each pc$^3$

$\phi(M_V)$ has units of $\frac{\# \text{ stars}}{\text{(magnitude interval)} \cdot \text{(volume)}}$
Flux-limited samples

• It’s very difficult to detect all stars in a given volume of space
• It’s much easier to detect all stars brighter than some flux (or apparent magnitude) cutoff
number observed in flux-limited survey $N(L)$

faint sources can only be seen if nearby (typically high density)

luminous sources can be seen to larger $d$ (typically low density)
While observing you detect all sources brighter than a flux of $f_{\text{min}}$. How far away can you detect a star with luminosity $L$?

or to rephrase:

At what maximum distance $D_{\text{max}}$ will a star with luminosity $L$ be detected if the minimum flux detectable is $f_{\text{min}}$?
while observing you detect all sources brighter than a flux of $f_{\text{min}}$. How far away can you detect a star with luminosity L?

or to rephrase, at what maximum distance $D_{\text{max}}$ will a star with luminosity L be detected if the minimum flux detectable is $f_{\text{min}}$?

$L = 4\pi D^2 f$

$D = (L/4\pi f)^{1/2}$

$D_{\text{max}} = (L/4\pi f_{\text{min}})^{1/2}$

inverse square law. this relation is true for a a source with any flux.

so it is also true for the minimum flux, and the minimum flux corresponds to the maximum distance that you can detect a source.
while observing you detect all sources brighter than a flux of $f_{\text{min}}$. how far away can you detect a star with luminosity $L$? or to rephrase, at what maximum distance $D_{\text{max}}$ will a star with luminosity $L$ be detected if the minimum flux detectable is $f_{\text{min}}$?

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inverse square law. this relation is true for a a source with any flux. so it is also true for the minimum flux, and the minimum flux corresponds to the maximum distance that you can detect a source.

what volume of space does this maximum distance correspond to?

$$V_{\text{max}}(L) = \frac{4\pi}{3} D_{\text{max}}^3 = \frac{4\pi}{3} \left( \frac{L}{4\pi f_{\text{min}}} \right)^{3/2}$$

volume surveyed is larger for luminous objects by $L^{3/2}$ this is the Malmquist bias (1925)!

a certain kind of selection bias
we observe $N(L)$ then need to divide by $V_{\text{max}}$ to get $\phi(L)$

$$\phi(L) = \frac{N(L)}{V_{\text{max}}(L)}$$

number observed in flux-limited survey

$1/V_{\text{max}} \propto L^{-3/2}$
Luminosity function of stars in Solar Neighborhood (within ~100 pc of Sun)

Most stars are much fainter than the Sun
luminosity function $\phi(L)$ or $\phi(M)$

what is the relative number of stars with different luminosities?

$\phi(M_V)$ how many stars of each absolute magnitude $M_V$ (or luminosity) exist in each pc$^3$

$\phi(M_V)$ has units of $\frac{\# \text{ stars}}{(\text{magnitude interval}) (\text{volume})}$
luminosity function $\phi(L)$ or $\phi(M)$
what is the relative number of stars with different luminosities?

$\phi(M_V) \Delta M_V =$ density of stars with absolute V-band magnitude between $M_V$ and $M_V + \Delta M_V$
 (#stars/volume)

SG fig 2-3 (histogram) shows (adopting $\Delta M_V=1$):

$$\phi(x) = \frac{\text{# stars with } M_V - 1/2 < x < M_V + 1/2}{\text{volume } V_{\text{max}}(M_V) \text{ over which these could have been seen}}$$
specific luminosity and mass density of stars
what is the light and mass contributed by stars with different luminosities?

$$\phi(M_V) \Delta M_V = \text{(specific) number density} \text{ of stars with}
\text{absolute V-band magnitude between } M_V \text{ and } M_V+\Delta M_V$$
(number/volume e.g., $#/\text{pc}^3$)

$$L_V \phi(M_V) \Delta M_V = \text{(specific) luminosity density} \text{ of stars}
\text{with absolute V-band magnitude between } M_V \text{ and } M_V+
\Delta M_V \text{ (luminosity/volume e.g., } L_{\text{sun}}/\text{pc}^3)$$

$$M \phi(M_V) \Delta M_V = \text{(specific) mass density} \text{ of stars with}
\text{absolute V-band magnitude between } M_V \text{ and } M_V+\Delta M_V$$
(mass/volume e.g., $M_{\text{sun}}/\text{pc}^3$)
What stars are we seeing in an optical image of a galaxy?

Most light from galaxies comes from a small number of very luminous stars.

Census of stars in the Solar Neighborhood of the Milky Way (within ~100 pc of Sun)
Most light from galaxies comes from a small number of very luminous stars.

Most (stellar) mass is in a large number of faint stars, *which are not directly detected.*
Which stars contain most of the stellar mass in a galaxy?

Most light from galaxies comes from a small number of very luminous stars.

Most (stellar) mass is in a large number of faint stars, which are not directly detected.

Census of stars in the Solar Neighborhood of the Milky Way (within ~100 pc of Sun)
Which stars contribute the most light and mass in a galaxy?

Most light from galaxies comes from a small number of very luminous stars. Most (stellar) mass is in a large number of faint stars, which are not directly detected.

Actual Census of stars in the Solar Neighborhood of the Milky Way (within ~100 pc of Sun)
What are implications for studying other galaxies??
Imagine a galaxy that hasn’t had any star formation recently. From which stars do most of its light arise?

A  massive main sequence stars
B  massive giant stars
C  intermediate-mass giant stars
D  intermediate-mass main sequence stars
Imagine a galaxy that hasn’t had any star formation recently. From which stars do most of its light arise?

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D  intermediate-mass main sequence stars
HR diagram of globular cluster

All the same age (& old)
Imagine a galaxy that **has had recent star formation**. From which stars do most of its light arise?

A  massive main sequence stars  
B  massive giant stars  
C  intermediate-mass giant stars  
D  intermediate-mass main sequence stars
Imagine a galaxy that **has had recent star formation**. From which stars do most of its light arise?

A  massive main sequence stars  
B  massive giant stars  
C  intermediate-mass giant stars  
D  intermediate-mass main sequence stars
HR diagram of nearby stars

HR diagram of globular cluster

Range of ages

All the same age (& old)
what stars produce most of the light in galaxies?

**spiral galaxy**
- old & young stars
- most of light from massive main sequence stars (blue) & less massive giant stars (yellow-red)

**elliptical galaxy**
- old stars
- most of light from less massive giant stars (yellow-red)
In solar neighborhood
initial LF is much higher than present LF for high mass (high L) stars
but initial LF is same as present LF for low mass (low L) stars
WHY??
Initial luminosity function

How many stars were born with each luminosity?

initial LF is different from present-day LF:

• Massive stars die quickly, so the only ones around are those that formed recently

• Low mass stars live for a long time, so all those which ever formed still exist
Initial luminosity function

How many stars were born with each luminosity?

\[ \Psi(M_V) = \Phi_{MS}(M_V) \]

\[ = \Phi_{MS}(M_V) \times \frac{\tau_{gal}}{\tau_{MS}(M_V)} \]

for \( \tau_{MS}(M_V) \geq \tau_{gal} \),

when \( \tau_{MS}(M_V) < \tau_{gal} \).

This factor corrects the observed number of massive stars for those that formed some time ago but have since died.

Makes overly simple assumption that star formation rate (SFR) has been uniform over time.
In solar neighborhood
initial LF is much higher than present LF for high mass (high L) stars
but initial LF is same as present LF for low mass (low L) stars
Initial mass function
convert luminosities to masses

\[ \xi(M) \Delta M = \xi_0 \left( \frac{M}{M_\odot} \right)^{-2.35} \left( \frac{\Delta M}{M_\odot} \right) \]

Sets local stellar density

This power law term is well-known oversimplification which gives “Salpeter initial mass function”

\[ \xi(M) \Delta M = (\text{specific}) \text{ number density of stars with mass between } M \text{ and } M+\Delta M \text{ (number/volume)} \]

\[ \mathcal{M} \xi(M) \Delta M = (\text{specific}) \text{ mass density of stars with mass between } M \text{ and } M+\Delta M \text{ (mass/volume)} \]
Stellar mass function of Pleiades star cluster
(close to initial mass function since cluster is young)

Histogram: observed number of stars per mass interval;
Solid red & black dotted lines – functions fit to data on number of stars
Dashed black line: “observed” mass of stars per mass interval
Most light from galaxies comes from a small number of very luminous stars.

Most (stellar) mass is in a large number of faint stars, which are not directly detected.
HR diagram of stars in Solar Neighborhood

- effective (Surface) temperature

30,000 K  6000K  3000K

30 $M_{\text{sun}}$

$1 M_{\text{sun}}$

$0.1 M_{\text{sun}}$

main sequence

giants

sun

L = $4\pi R^2 \sigma_{SB} T^4$ for stars

giants have larger radius for same T

how to get L: measure flux (or brightness), figure out distance --> get L from $L = 4\pi D^2 f$