The Great Debate: *The Size of the Universe* (1920)

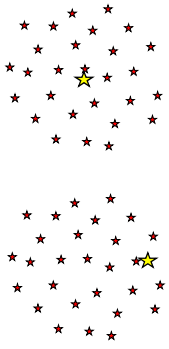
Heber Curtis

- Our Galaxy is rather small, with Sun near the center.
  - 30,000 LY diameter.
- Universe composed of many separate galaxies
  - Spiral nebulae = "island universes"

Harlow Shapley

- Our Galaxy is very large, with Sun far from center.
  - 300,000 LY diameter.
  - Sun 60,000 LY from center.
- Spiral Nebulae are inside our galaxy.
  - "nova" magnitudes
  - "Proper motion" ➔ rapid rotation.

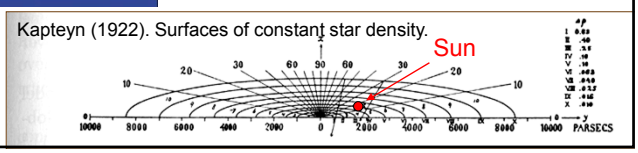
Counting Stars:



Sun near center of small universe.

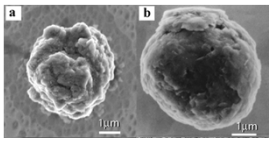
Mapping our Galaxy up until ~1920

Lick 36" Refractor 1888



Dust [12.1]

- Tiny grains (≤ 1μm)

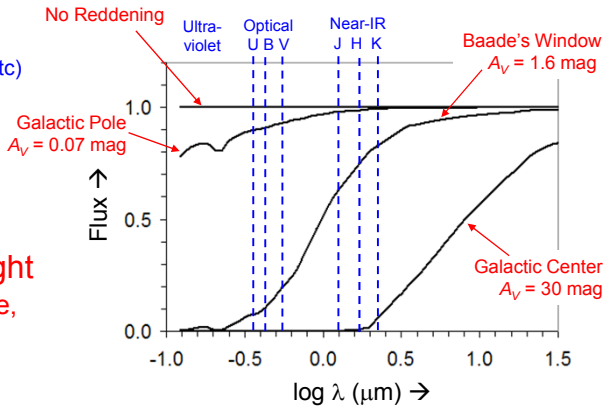


- Cores consisting of
  - Graphite
  - or Silicates

($Mg_xFe_{1-x}SiO_3$; $Mg_{2x}Fe_{2-2x}SiO_4$; etc)

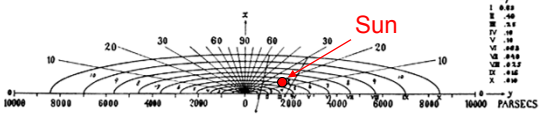
- Ices can condense on surface:
  - C,O combined with H

- Absorb and scatter light
  - Effect strongest in blue,
  - less in red,
  - zero in radio.



Mapping Our Galaxy

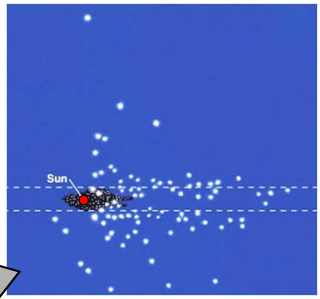
From star counts:



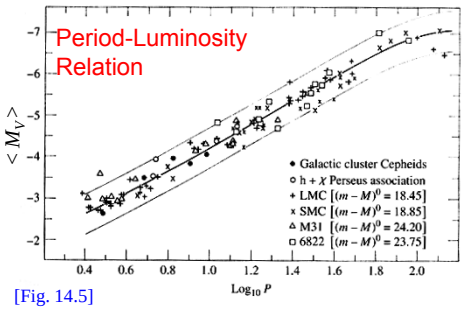
Kapteyn (1922). Surfaces of constant star density.

From distribution of Globular Clusters:

- Use pulsating variables to find clusters' distances.
- Clusters are out of MW disk ➔ little reddening.



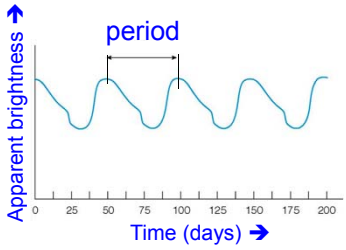
Shapley (1920) Globular Clusters
(distances using RR-Lyraes)

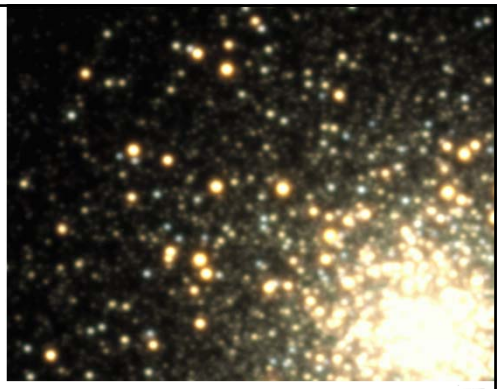


[Fig. 14.5]

Pulsating Variable Stars

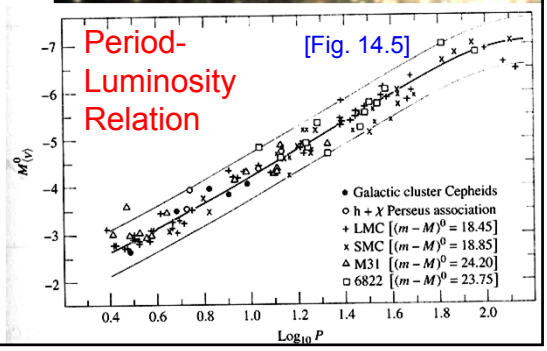
- These stars regularly expand & contract.
- Like a big spring.
- Change in size ➔
  - change in temperature
  - change in luminosity

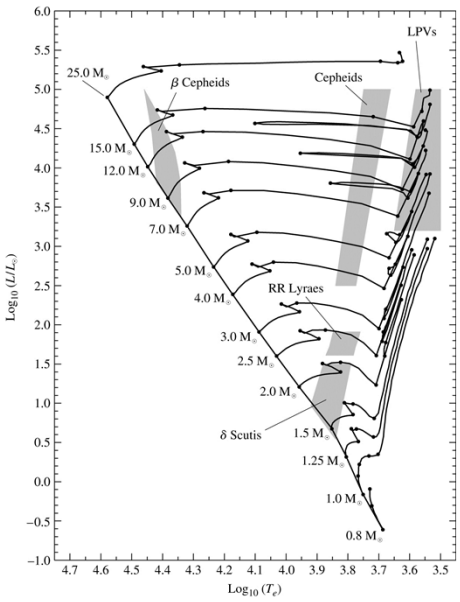


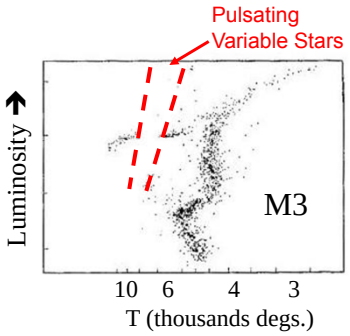


P-L relation

- discovered in Magellanic Clouds
- calibrated locally, using (statistical) parallaxes





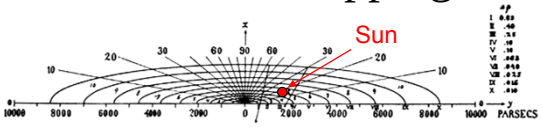


The Instability Strip

- In populations of old stars.
- For example, Globular Clusters
- Occurs during He burning

Mapping Our Galaxy

From star counts:



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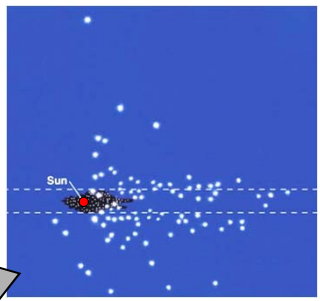

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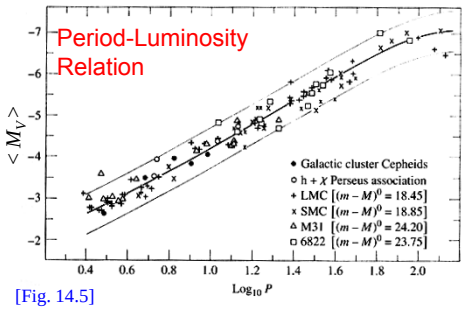
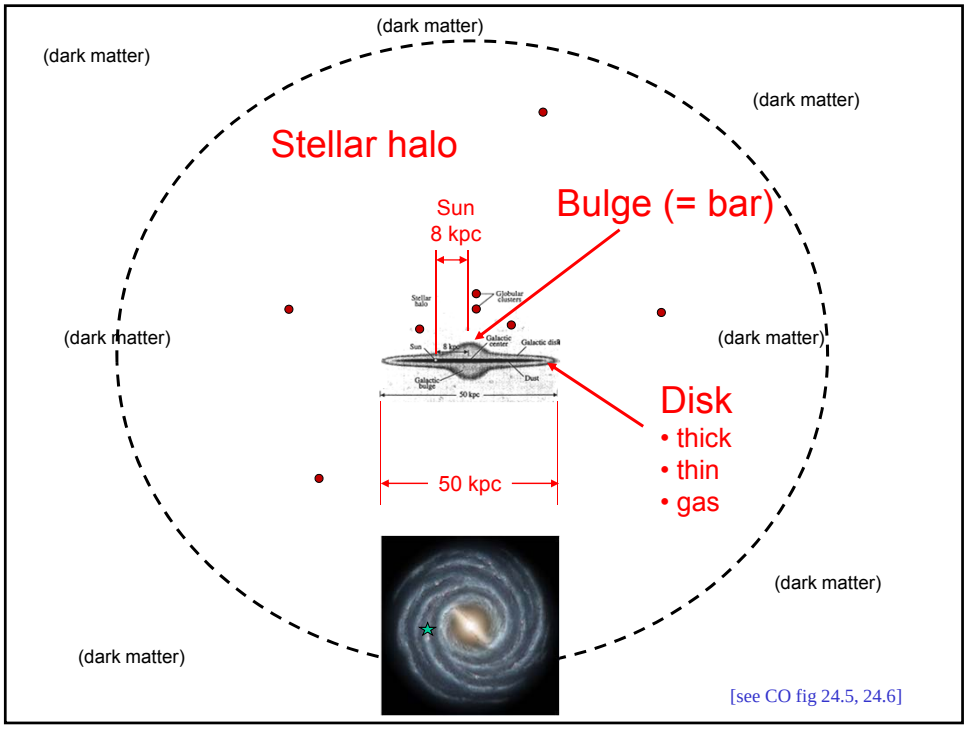


[Fig. 14.5]



[see CO fig 24.5, 24.6]

[Table 24.1]

Disks

	Neutral Gas	Thin Disk	Thick Disk
M (10^{10} $M_\odot$)	0.5[a]	6	0.2 to 0.4
L_B (10^{10} $L_\odot$)[b]	—	1.8	0.02
M/L_B ($M_\odot/L_\odot$)	—	3	—
Radius (kpc)	25	25	25
Form	e^{-z/h_z}	e^{-z/h_z}	e^{-z/h_z}
Scale height (kpc)	< 0.1	0.35	1
σ_w (km s^{-1})	5	16	35
[Fe/H]	> +0.1	−0.5 to +0.3	−2.2 to −0.5
Age (Gyr)	$\lesssim$ 10	8[c]	10[d]

Spheroids

	Central Bulge[e]	Stellar Halo	Dark-Matter Halo
M (10^{10} $M_\odot$)	1	0.3	190^{+360}_{-170}[f]
L_B (10^{10} $L_\odot$)[b]	0.3	0.1	0
M/L_B ($M_\odot/L_\odot$)	3	~ 1	—
Radius (kpc)	4	> 100	> 230
Form	boxy with bar	$r^{-3.5}$	$(r/a)^{-1}(1+r/a)^{-2}$
Scale height (kpc)	0.1 to 0.5[g]	3	170
σ_w (km s^{-1})	55 to 130[h]	95	—
[Fe/H]	−2 to 0.5	< −5.4 to −0.5	—
Age (Gyr)	< 0.2 to 10	11 to 13	~ 13.5

Usually see deVaucouleurs' $r^{1/4}$ surface brightness law:

$$\log_{10}\left[\frac{I(r)}{I_e}\right] = -3.3307\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]$$

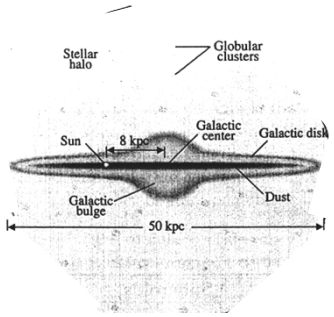
Milky Way's Morphology

Exponential disk

$$n(z,r) = n_o(e^{-z/z_{thin}} + 0.02e^{-z/z_{thick}})e^{-r/h_r}$$

+ spheroids with various "forms"

$n = n_o \times form$



[Fe/H] =log(Fe/H) abundance ratio relative to Sun

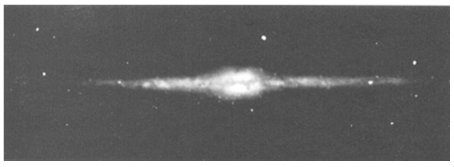
Milky Way Bulge

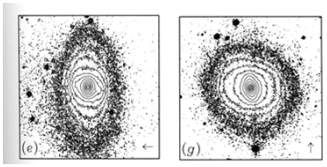
- Roughly follows DeV profile ($r^{1/4}$ law)

$$\log_{10}\left[\frac{I(r)}{I_e}\right] = -3.3307\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]$$

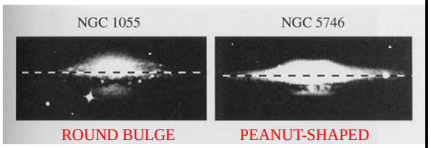
- Elongated
  - Minor/major ~0.6
- Now thought to include a bar
  - Expanding 3kpc arm
    - H I feature
    - v_r = -50 km/s
    - Elliptical orbit due to bar
- ~10^{10} $M_\odot$
- Range in metallicity
  - -2 < [Fe/H] < +0.5
  - Baade's window

< [Fe/H] < +0.5





SB0 isophotes [BM] Fig 4.57

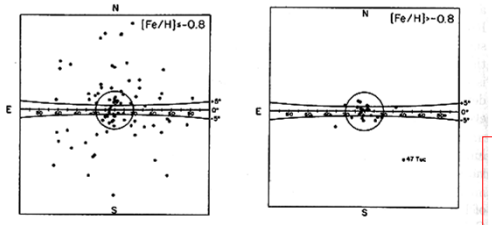


The Psychedelic Barred Spiral Movie

[CO fig. 24.5]

Milky Way Halo

- Globular clusters + field stars
- Field stars = high velocity stars
- ~150 globular clusters known, in 2 different systems:
  - Older (~13 Gyr)
    - Very metal-poor (-2.5 < [Fe/H] < -0.8)
    - Spherical distribution around galactic center
    - No net rotation



[Fig 24.12]

  - Younger
    - (~11Gy, ~ same as thick disk)
    - Moderate metallicity ([Fe/H]> -0.8)
    - Compare to thick disk –0.6 < [Fe/H] < -0.4
    - Flattened
    - Show net rotation => part of thick disk??

Warning! These are plots of directions in sky, NOT cross-sections of MW

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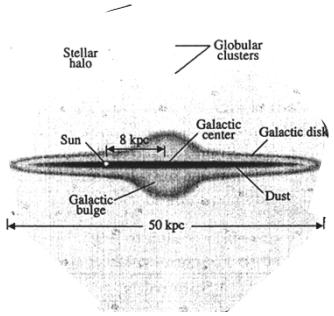


[Fe/H] =log(Fe/H) abundance ratio relative to Sun

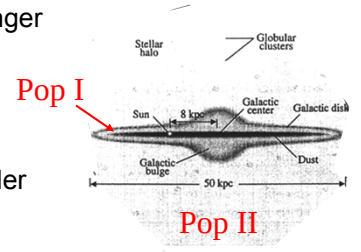
Stellar Populations

Baade (1944)

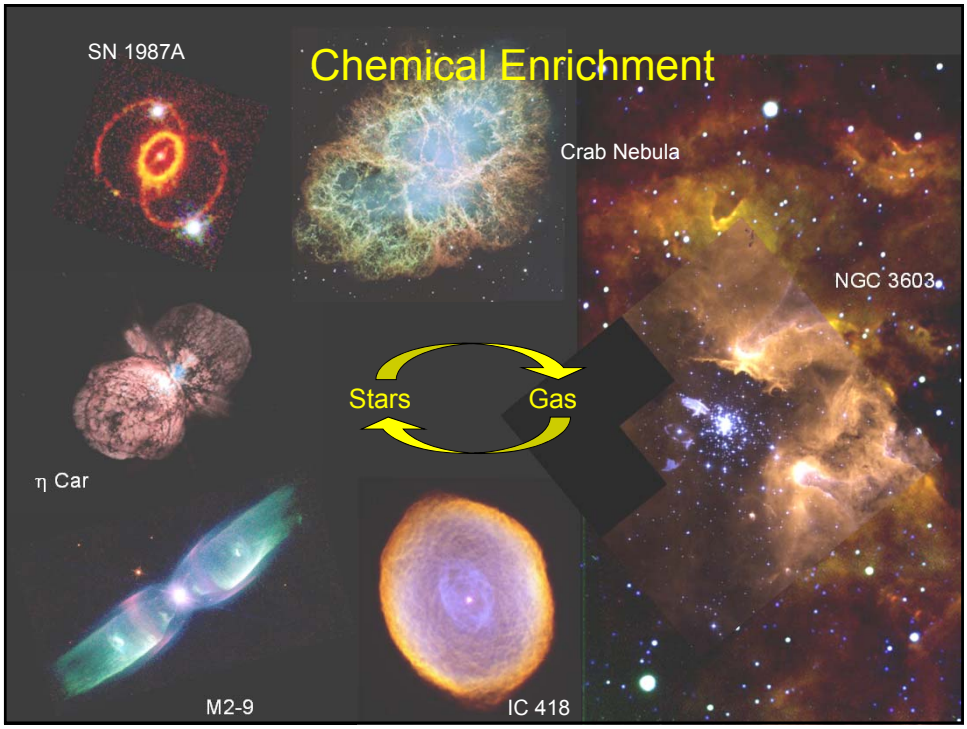
- Abundances
- Kinematics
- Ages

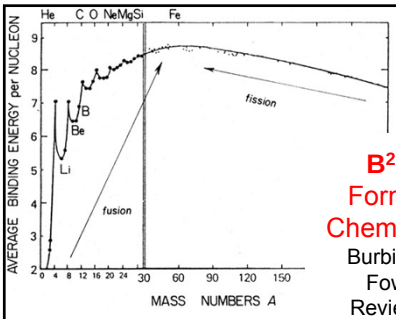
X,Y,Z = mass fractions
X ~ 0.73 (H)
Y ~ 0.25 (He)
Z ~ 0.02 (metals)

- Pop I : Metal rich (Z ~ 0.02), disk, younger
  - Disk field stars (up to 10-12 Gyr old)
  - Open clusters
  - Gas
  - Star formation regions
- Pop II: Metal poor (Z ~ 0.001), halo, older
  - Globular clusters (12-15 Gyr)
  - Halo field stars
  - Bulge??? ….but includes metal rich stars.
- Abundance Determinations
  - Stellar spectroscopy
    - [Fe/H], etc. ➔ $\log(N_{Fe}/N_H)$ – log(solar)
    - Iron ejected by Sne Ia after about 10^9 yrs.
    - Iron often used as tracer of *all* metals.
  - Stellar colors
  - HII regions

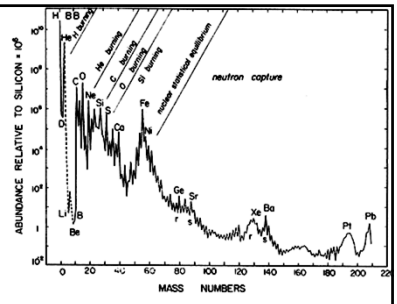


	[Fe/H]
Thin Disk	-0.5➔ +0.3
Thick Disk	-2.2➔ -0.5
Halo	-5.4➔ -0.5
Bulge	-2.0➔+0.5





B²FH (1957)
Formation of the Chemical Elements
Burbidge, Burbidge, Fowler & Hoyle. Reviews of Modern Physics, 29, 547.



Gradual processes in Interiors of Stars
- H burning (4H ➔ He)
- α process (C,O,Ne,Mg,Si,S…)
- s process
  - slow neutron capture, relative to beta-decay timescale

Supernovae
- e process
  - nuclear statistical equilibrium
  - iron peak elements
- r process
  - rapid neutron capture