Astronomy 330

Lecture 6

22 Sep 2010

Outline

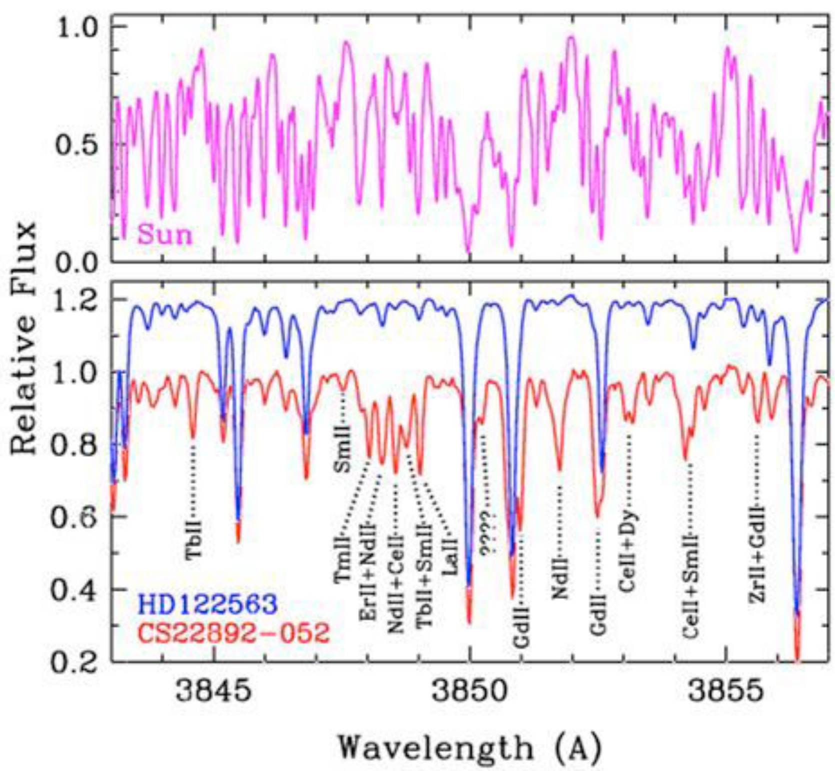
- Review & conclude:
  - ISM detection techniques
  - Chemical evolution
- Stellar Luminosity Function
- The Milky Way as Galaxy:
  - Stellar Luminosity Function
  - Size and structure: bars, truncation
  - Kinematics: disk rotation

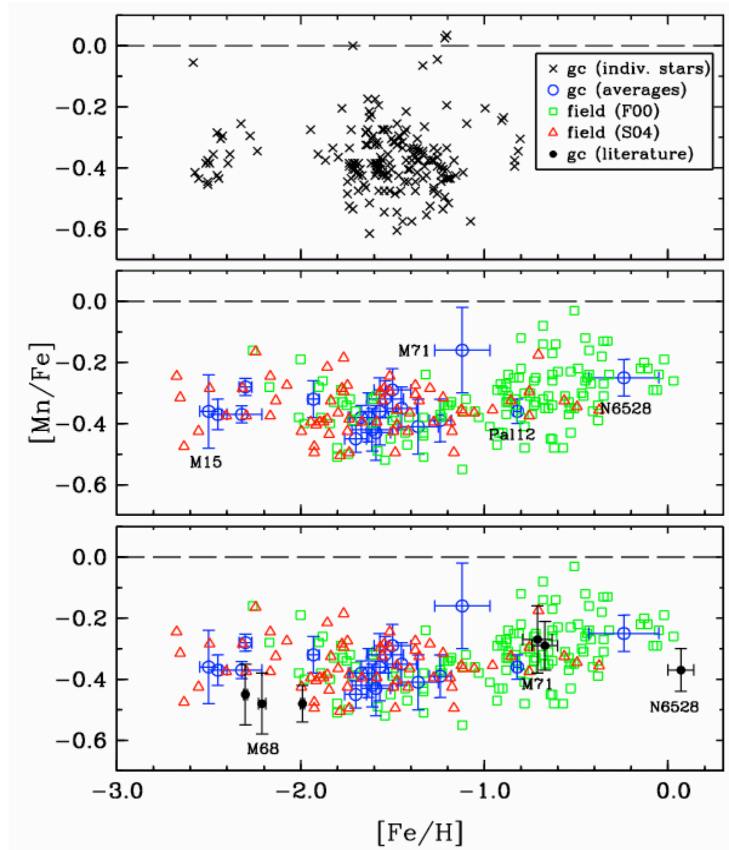
Review: ISM

- Gas content of disk galaxies
  - Phases: cold, cool, warm, hot
  - Filling-factors
  - Densities
  - Detection methods:
    - CO (mm)
    - HI (21cm)
    - HII (Ha, [OII],etc.)
    - X-ray emission
  - Diagnostics: SFR, T_e, n_e, shocks
- Origin of the diffuse hot gas in galaxies
  - Likely from SNe
  - Hot gas is correlated with star formation/spiral arms in disk galaxies

Review: Chemical Evolution

- What is the correlation between these observed absorption lines and the star formation history of this stellar system?



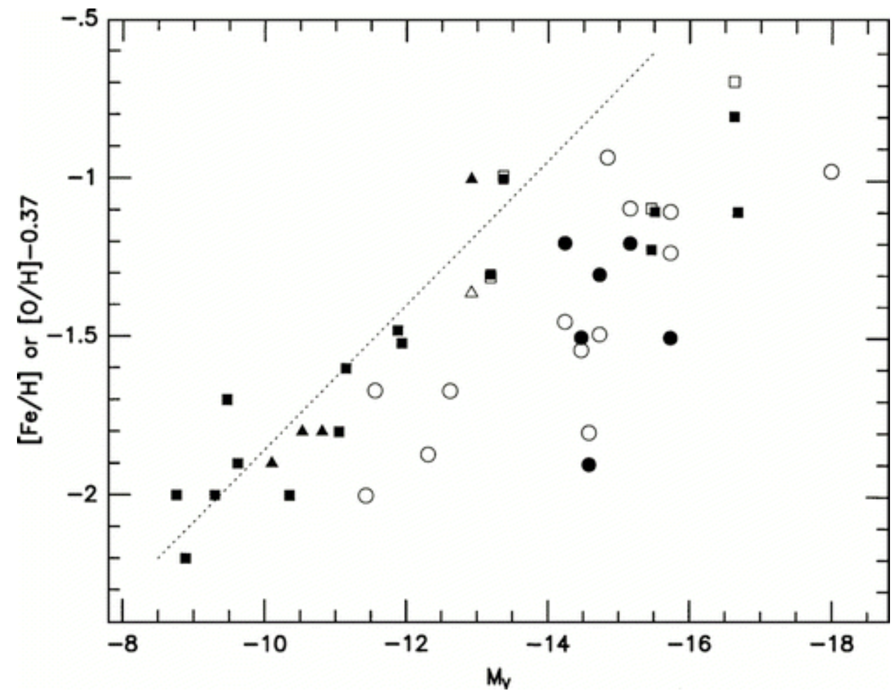


Recall: Disk Gradients

- General characteristics
  - $12 + \log(O/H) = 8.58 - 0.32\ R/R_0$
  - Generally: -0.04 to -0.07 dex/kpc
  - Flatter in late-types, steep in barred galaxies
- Why are there gradients?
  - Radial dependence on SFR/SFH?
  - Radial gas flows?
  - Radial dependence on yield?
  - Radial dependence on infalling gas?

Extragalactic Abundances: Dwarfs

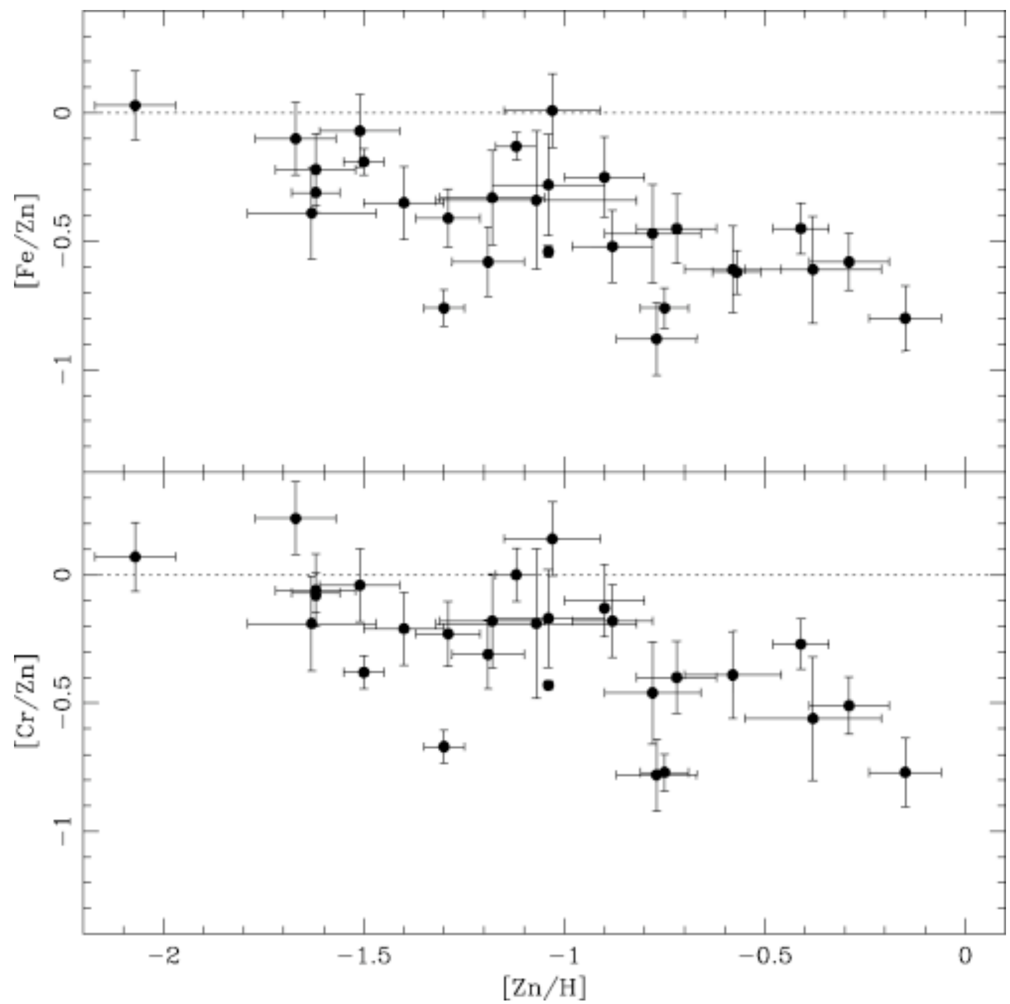
- LMC is 50-70% solar
  - [O/H] = -0.3 to -0.15
- SMC ~ 20-25% solar
  - [O/H] = -0.7 to -0.65
- Some dwarfs extremely metal poor (1/10 solar)
- Why?



Decreasing luminosity

QSO Absorption Lines

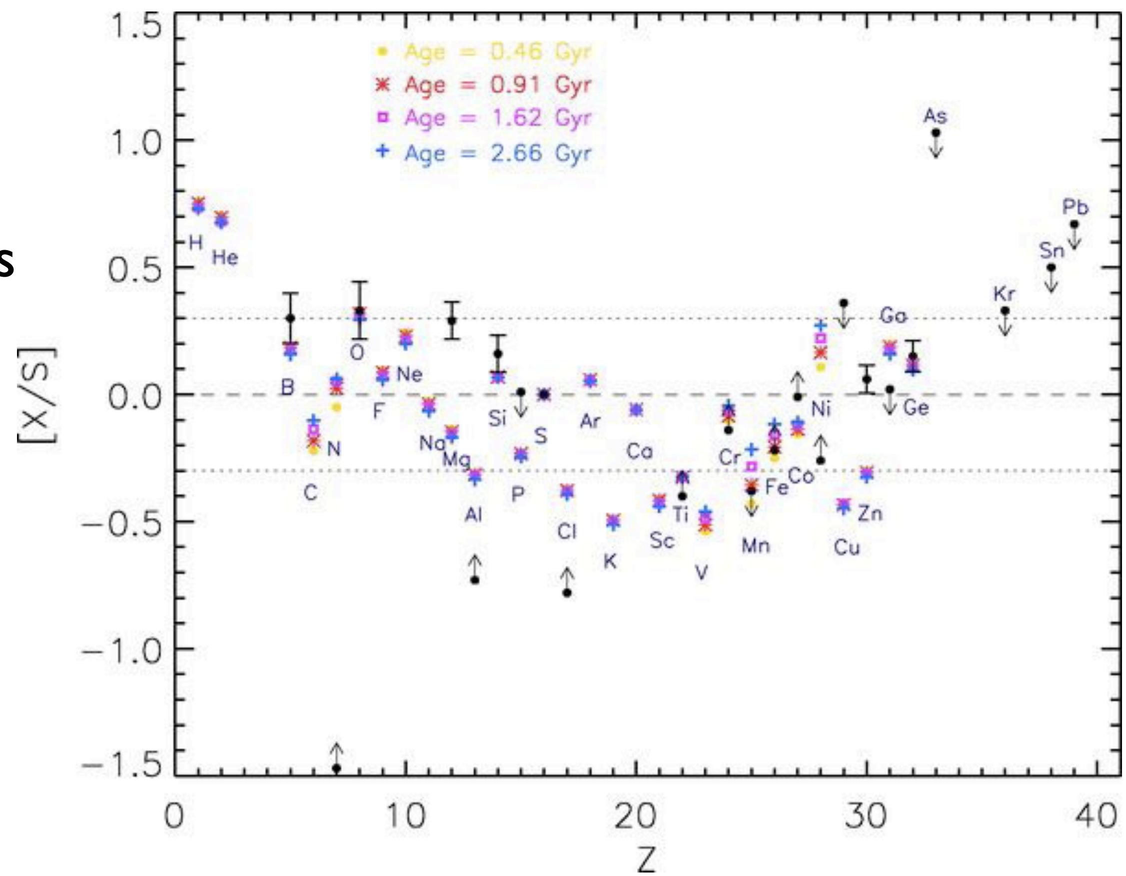
- Absorption line systems detected against background quasars
- Gas phase abundances can be measured via absorption lines
- Most metal-poor gas systems ever found
- Enrichment histories vary from solar



Lanfranchi & Friaca 2003

QSO Absorption Lines

- Damped Ly-α systems have high column, high velocities ➔ correlated with galaxies
- Thought to be progenitors of today's massive galaxies
- Consistent with:
  - young ages
  - 1/3 solar
  - Enrichment dominated by massive stars
    - few Type-Ia SNe



Fenner, Prochaska, & Gibson 2004 ApJ

Chemical Evolution of Galaxies

- Simple models
  - $M_g(t)$ = gas mass
  - $M_r(t)$ = remnant mass
  - M_s= mass in stars
  - $M_h(t)$ = mass in heavy elements
  - $Z(t) = M_h/M_g$= metallicity
  - ΔM = change in mass
  - p = fractional yield of heavy elements

➔

$$\Delta M_h = p\Delta M_s - Z\Delta M_s$$
$$= (p-Z)\Delta M_s$$
$$\Delta Z = \Delta (M_h/M_g)$$
$$= [p\Delta M_s - Z(\Delta M_s + \Delta M_g)]/M_g$$

See S&G 4.3.2

- In a closed box $\Delta M_s + \Delta M_g = 0$…..
  - $Z(t) = p \ln [M_g(t)/M_g(0)]$
  - Implies gas-rich things should have lower Z
  - Also: $M_s(<Z(t)) = M_g(0)[1 - e^{-Z(t)/p}]$ ➔

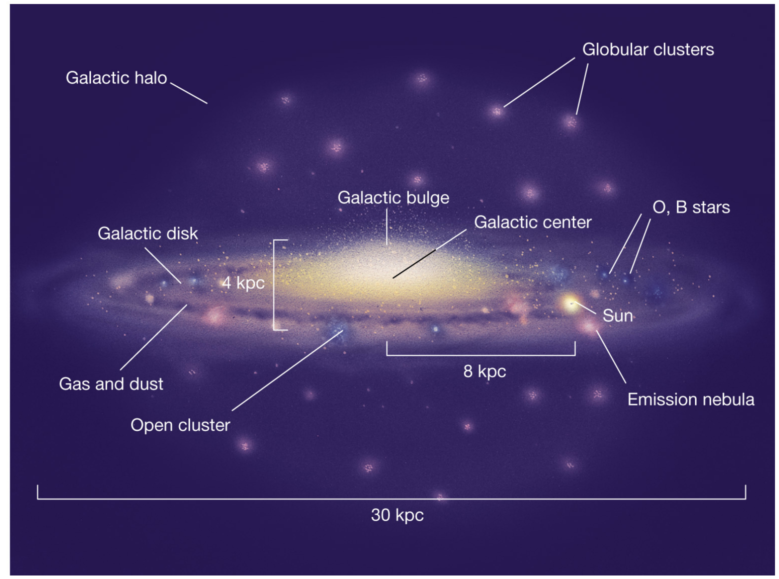
- We should see lots of really low metallicity G stars
- Something like 50% of G dwarfs should have $z < 0.25 Z_\odot$!
- But we don't: closer to 25% for Fe and <1% for O
- ➔ so-called G-dwarf problem

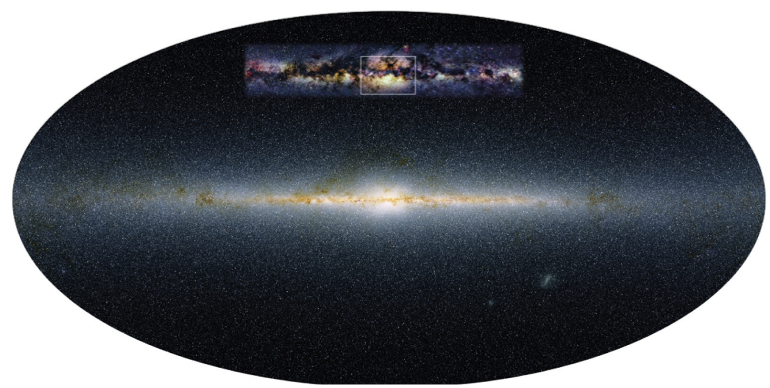
The G-Dwarf Problem

- How does the absence of low-metallicity G-dwarfs in the solar neighborhood relate to a few other conundrums mentioned so far:
  - The mysterious absence of detected Pop III stars?
  - The puzzling fact that most of the baryons do not appear to be in galaxies, but in a hot (10^6 K gas) in the IGM?
  - And the baryonic IGM is metal-enriched?

Modeling the Milky Way Galaxy (MWG)

- What is the stellar distribution?
- How big is the Milky Way?
  - Does (where does) the disk have an outer truncation?
- Does it have a bar?
- How do the stars move in the galaxy?
  - Galactic rotation and Oort's constants



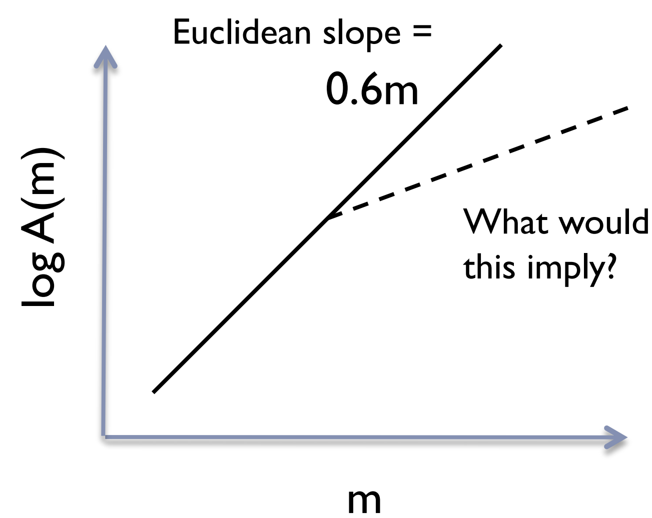


Star Counts

- Formalism
  - $N(M,S)=\int \Phi(M,S)D(r)r^2dr$
    - N = # of field stars of a given absolute magnitude (M) and spectral type (S) in the galaxy
    - Φ = stellar luminosity function (# pc^{-3} for some spectral type)
    - D(r) = density distribution
      - may also depend on M,S: D(r,M,S)
      - Alternatively, Φ may also depend on r
- The simplest thing we can actually observe:
  - A(m) = # of stars of some apparent magnitude, m.
  - $A(m) = \int \Phi(M)\, D(r)\, \Omega\, r^2\, dr$
    - Ω = solid angle of survey
- If we have colors, we might get a crude A(m,S)
  - but without distances or some luminosity indicator, we can't break the dwarf-giant degeneracy (e.g., K V vs K III).

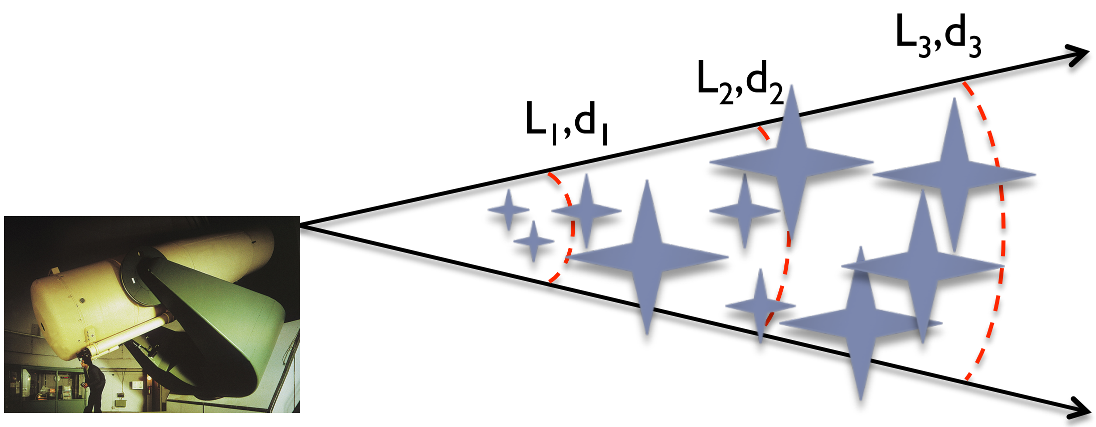
Star Counts: Infinite Euclidean Universe

- A(m) represents the differential counts, i.e., number of stars per apparent magnitude interval
- Knowing the geometry (locally Euclidean), the count slope (dA/dm) tells us about the spatial distribution of sources.
- For a *uniform* space-distribution of sources it is straightfoward to show
  - $d(\log A)/dm = 0.6m + \text{constant}$
- This leads to Olbers' paradox:
  - $l(m) = l_0 d\exp(-0.4m)$
  - $L(m) = l(m)A(m)$
  - $L_{tot} = \int l(m)A(m)\, dm = \infty$
- The distribution of stars in the galaxy must be spatially finite
- *What about the universe of galaxies?*



The Malmquist Bias & the Night Sky

- What stars do you see when you look up at the night-time sky?
- Does this make sense given what you know about the HR diagram
- Malmquist bias:
  - You can see brighter objects farther away to a fixed m
  - Volume increases as d^3



For a uniform space-density, the observer is biased toward finding intrinsically luminous objects.

young

old

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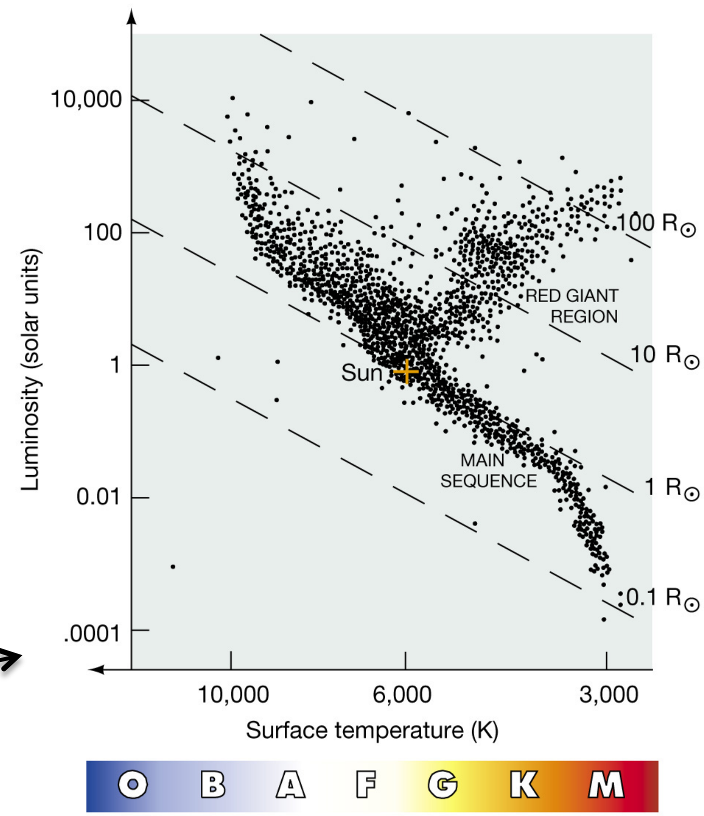

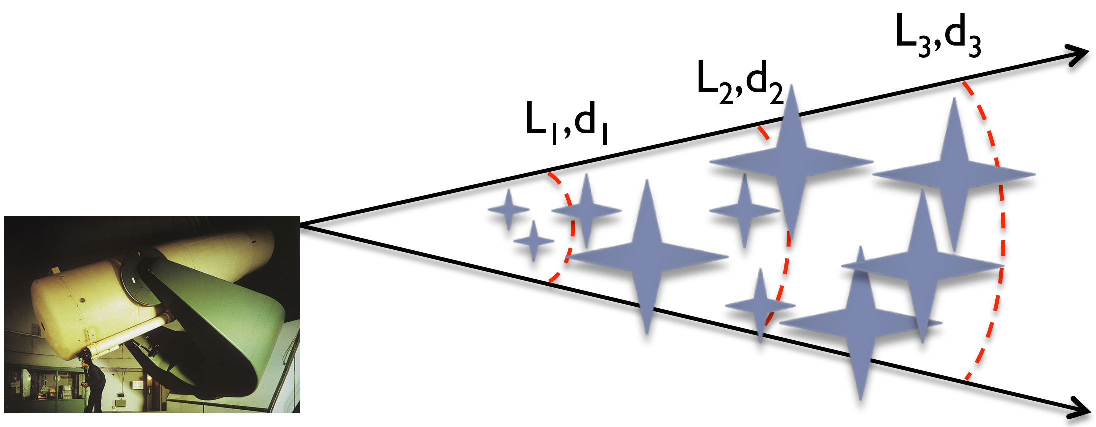

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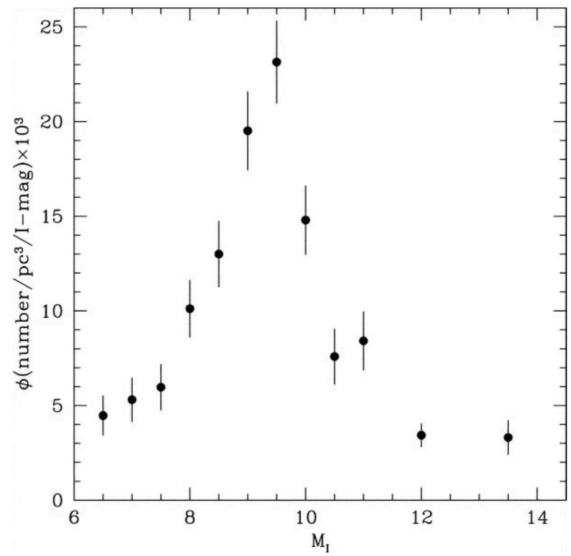
Star Counts & The Malmquist Bias

- What's the mean magnitude of stars with apparent magnitude, m?
  - $M(m) = \int M\Phi(M)D(r)r^2dr \,/\, \int \Phi(M)D(r)r^2dr$
  - Recall $A(m) = \int \Phi(M)\, D(r)\Omega r^2dr$
- Assume the stellar luminosity function (LF) is Gaussian for a given spectral type:
  - $\Phi(M,S) = \Phi_0/(2\pi)^{1/2}\sigma \exp[-(M-M_0)^2/2\sigma^2]$
  - M_0= mean magnitude
  - Φ_0= # pc^{-3} for some spectral type
  - σ is the distribution width



Zheng et al. (2004, ApJ, 601 500): MW disk M-dwarfs, *I*-band, *HST*

Star Counts & The Malmquist Bias

- Push through the integral for M(m) and move things around a bit….
  - $M(m) = M_0 – [\sigma^2/A(m,S)]\ [dA(m,S)/dm]$
  - Or:

$$M(m) – M_0 = - \sigma^2\, d \ln A / dm$$

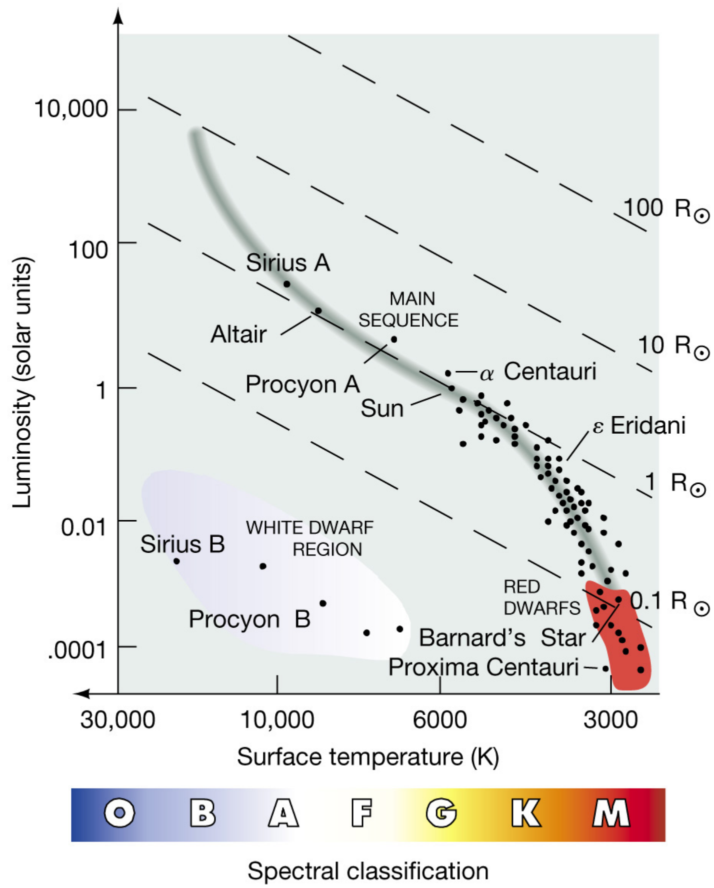
This is for the specific case of a Gaussian LF, but it can be generalized.

- If there are more stars at faint magnitudes, then the stars at some m are more luminous than the average for all stars in a given volume
  - This will come back to bite us with a vengeance when considering distant galaxy counts

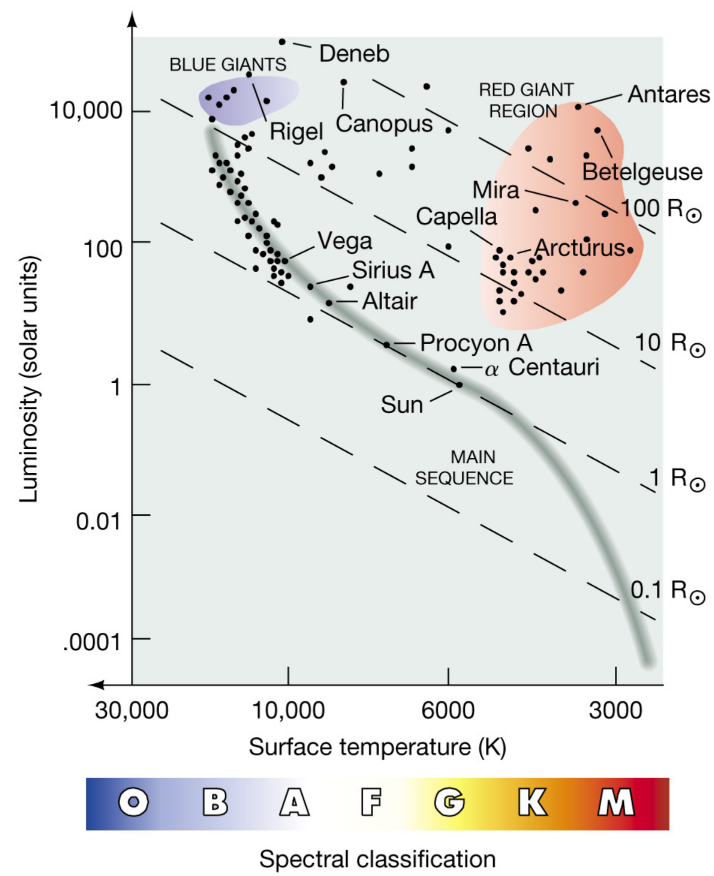
A note on logarithmic derivatives:
$d \ln x = dx / x$
This is nice because it normalizes the gradient to the amplitude of the signal, i.e., dimensionless. Therefore often used in Astronomy

Space Densities: Local Neighborhood

Volume-limited



Brightness-limited

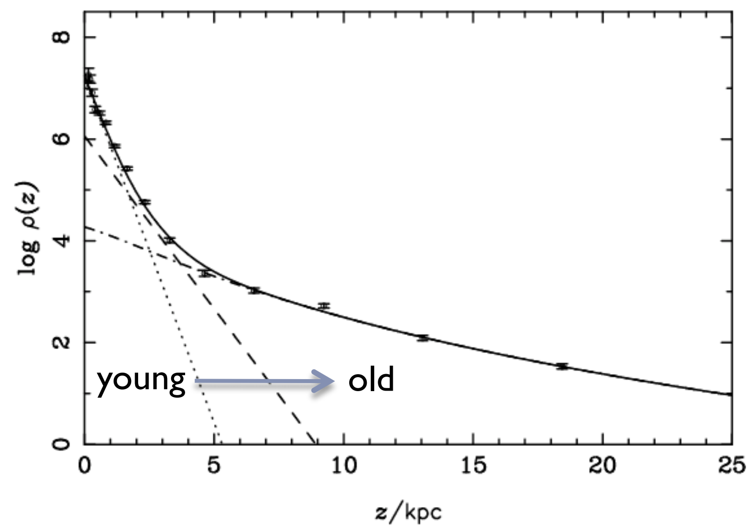


Stellar Luminosity Function

- Measure for a distance(volume)-limited sample
- Bahcall & Soneira (1980) used:
  - $\Phi(M) = [n_* 10^{\beta(M-M_*)}] / [1+10^{-(\alpha-\beta)\delta(M-M_*)}]^{1/\delta}$
    - $n_* = 4.03 \times 10^{-3}$
    - $M_* = 1.28$
    - $\alpha = 0.74$, $\beta = 0.04$, $1/\delta = 3.40$
- See also Figure 2.4 in S&G.
- Basic results
  - 10^5 times more G stars than O stars
  - Nearby stars tend to be
    - low-luminosity and apparently faint
  - Average $M/L = 0.67\ (M/L)_\odot$

Star Counts: The Disk

- Star counts (z direction)
  - n(z) proportional to $\exp(-z/z_0(m))$,
    - $z_0(m)$ is the scale height (and, yes, it does vary with magnitude)
  - More importantly, z_0 varies with spectral type:
    - young : old ➔ small : large
    - **WHY?**
  - Reid & Majewski (1993)
    - Thin disk with z_0= 325 pc – Pop I
    - Thick disk with z_0= 1200 pc – Pop II
- The Disk
  - $I(R) = I(0)\exp[-R/h_R]$
  - tough to measure in our own galaxy, but measurable in other disks pretty easily.
- Disk is really a double exponential:
  - $I(R,z) = I(0,0)\exp(-z/z_0-R/h_R)$



Du et al. 2003 A&A 407 541, stellar density perpendicular to the plane

Star Counts: The Halo

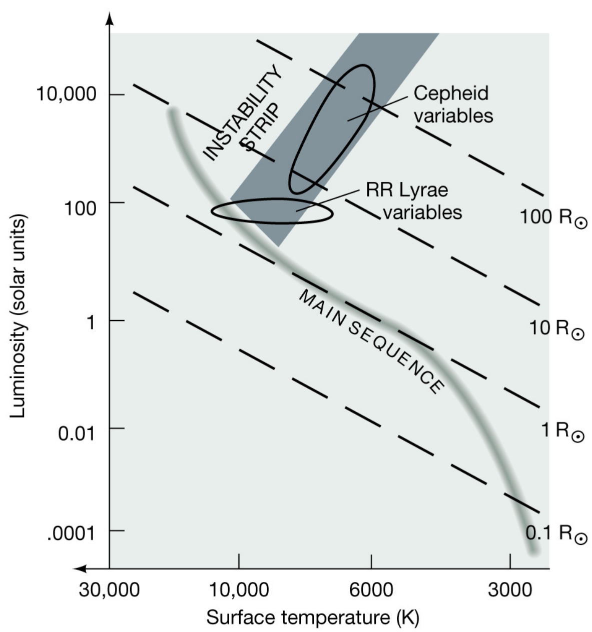
- Halo stars
  - Halo stars are faint, need an easy to find tracer

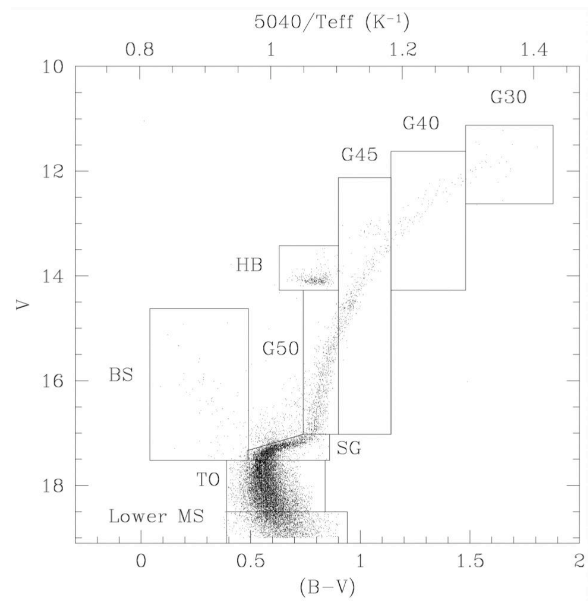
RR Lyrae stars

  - Stellar density falls off as r^{-3}
  - Looks like the distribution of globular clusters, which you also get from RR Lyrae stars
- We will come back to this density fall-off when we consider the rotation curve.

Recall: RR Lyrae Stars

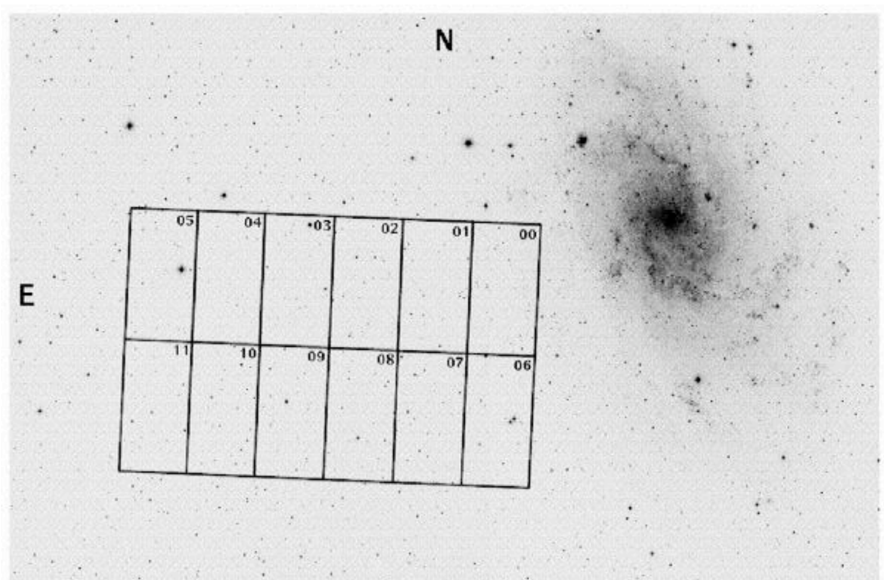
- HB stars in "the instability strip"
  - Solar mass
  - Opacity driven pulsations yield variability which is correlated with M
  - M = -2.3±0.2 log(P) –0.88±0.06 (with some additional variation due to metallicity)
  - Old, low mass stars (hence good tracers of the halo)
- Higher mass (farther up the instability strip you'll find Cepheids)

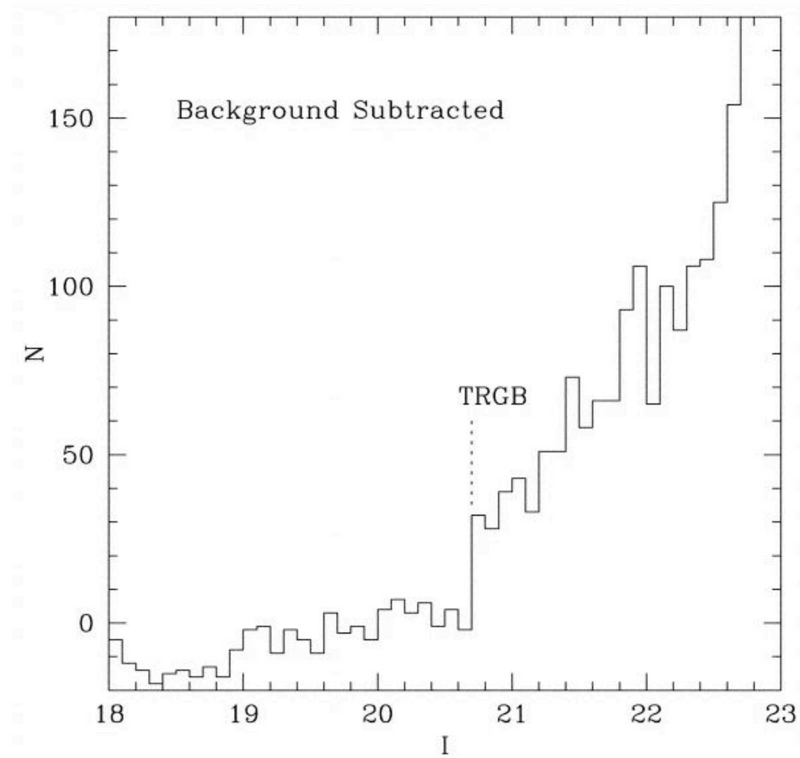




M33 LF

- Outer fields of M33
  - (Brooks et al. 2004, AJ, 128, 237)



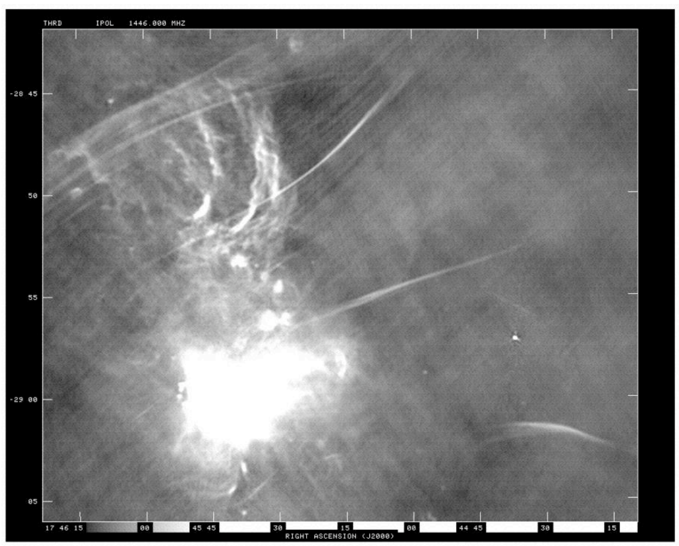


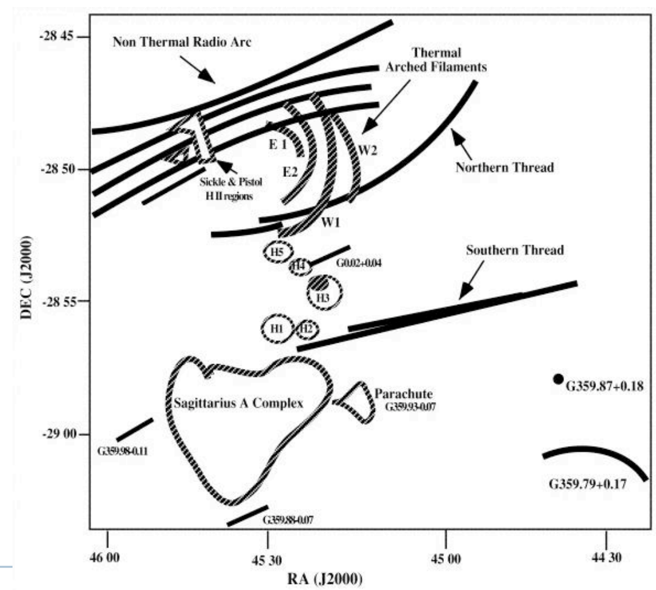
Counts proportional to luminosity function of *all* stars in M33 halo, corrected for contamination and completeness. TRGB at I = 20.7 gives distance modulus.

Galactic Center

- We'll talk about the center again when we discuss AGNs
- The optical view:

- The VLA 1.4 Ghz view:





Galactic Center: Distance

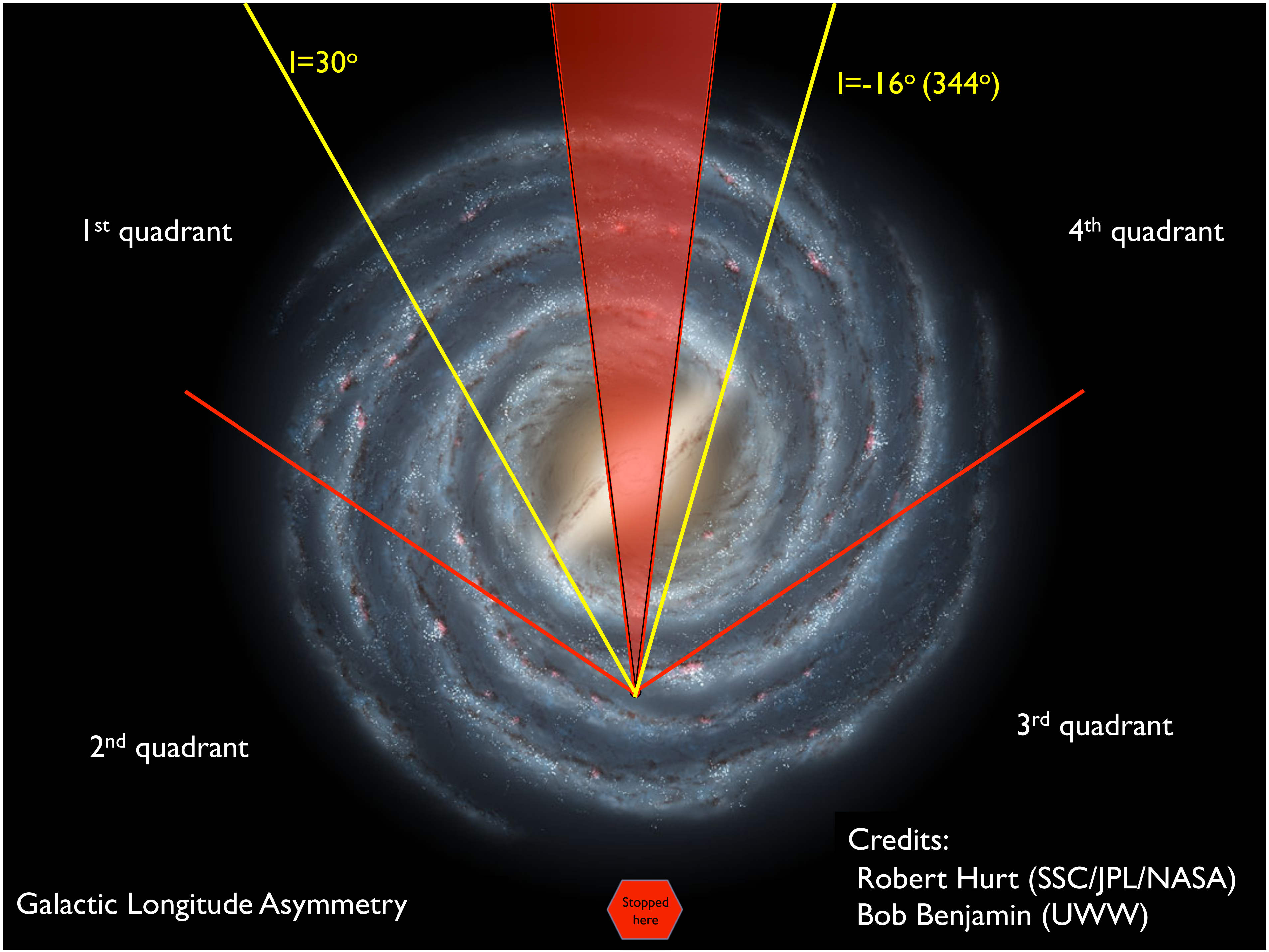
- Use RR Lyraes + other stellar tracers
  - Use the globular cluster population, OH/IR stars in the bulge
  - Get mean distances ➔ 8.5 kpc
- Proper motion studies of Sgr A*
  - Look for maser emission
  - Follow maser proper motion + observed velocity

    ➔ distance (7.5 kpc)

Galactic Bar

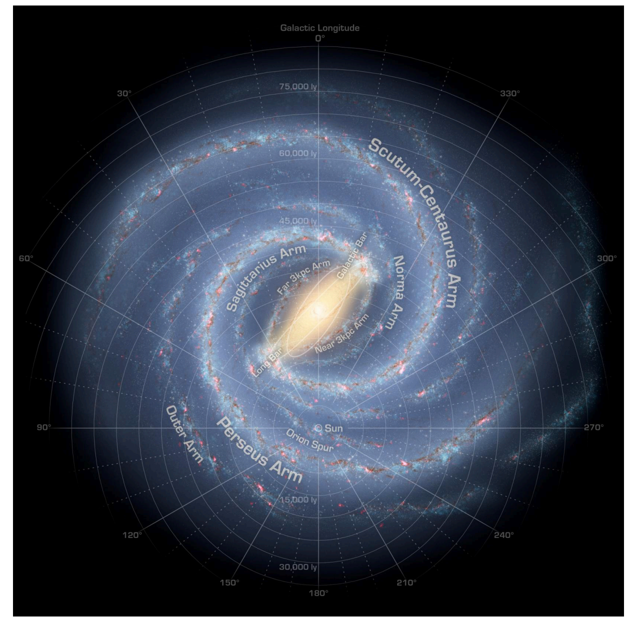
- Lots of other disk galaxies have a central bar (elongated structure). Does the Milky Way?
- Photometry – what does the stellar distribution in the center of the Galaxy look like?
  - Bar-like distribution: $N = N_0 \exp(-0.5r^2)$, where $r^2 = (x^2+y^2)/R^2 + z^2/z_0^2$
  - Observe A(m) as a function of Galactic coordinates (l,b)
  - Use N as an estimate of your source distribution:
    - counts A(m,l,b) appear bar-like
  - Sevenster (1990s) found overabundance of OH/IR stars in 1^{st}quadrant. Asymmetry is also seen in RR Lyrae distribution.
- Gas kinematics: $V_c(r) = (4\pi G \rho /3)^{1/2} r$

  ➔ we should see a straight-line trend of $V_c(r)$ with r through the center (we don't).
- Stellar kinematics – again use a population of easily identifiable stars whose velocity you can measure (e.g. OH/IR stars).
  - Similar result to gas.


l=30°
l=-16° (344°)
1st quadrant
4th quadrant
2nd quadrant
3rd quadrant
Stopped here
Galactic Longitude Asymmetry
Credits:
Robert Hurt (SSC/JPL/NASA)
Bob Benjamin (UWW)

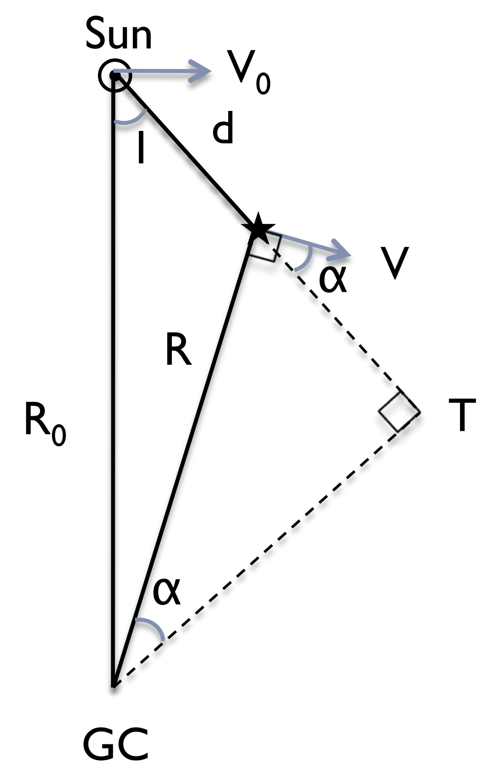
Galactic Rotation: A Simple Picture

- Imagine two stars in the Galactic disk; the Sun at distance R_0, the other at a distance R from the center and a distance, d, from the Sun. The angle between the Galactic Center (GC) and the star is l, and the angle between the motion of the stars and the vector connecting the star and the Sun is α. The Sun moves with velocity, V_0, and the other star moves with velocity, V.
  - See Figure 2.19 in S&G.



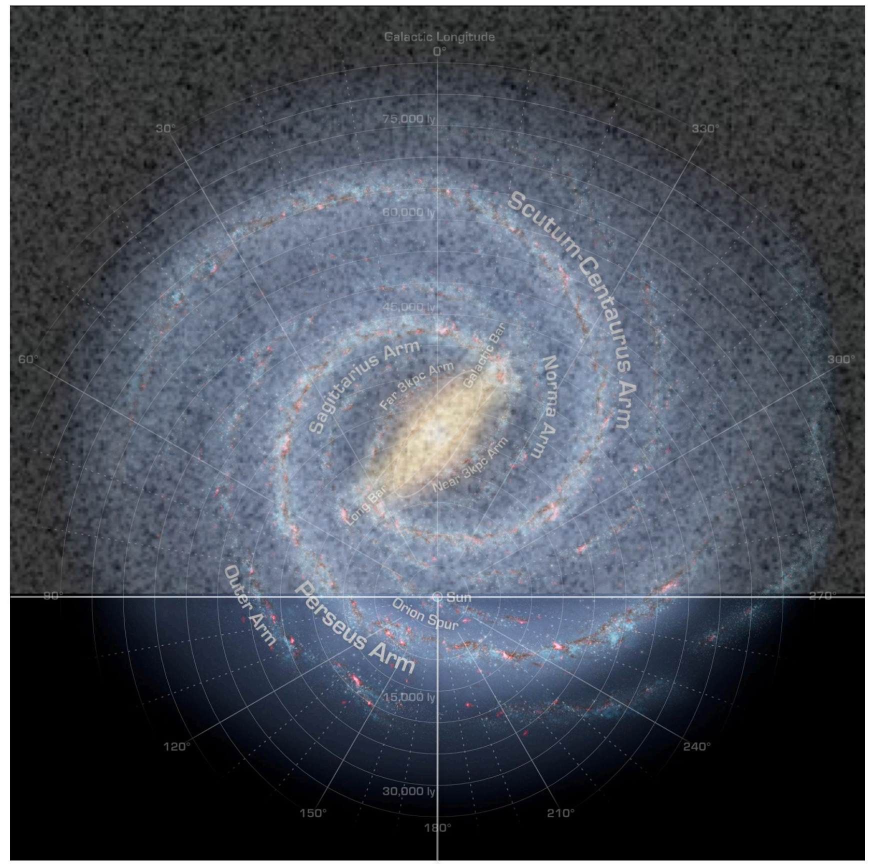
Relative motion of stars

- Radial velocity of the star
  - $V_r = V \cos\alpha - V_0 \sin l$
  - now use law of sines to get…
  - $V_r = (\omega_* - \omega_0)\, R_0 \sin l$,
    - ω is the angular velocity defined as V/R.
    - l is the Galactic longitude
- Transverse velocity of the star
  - $V_T = (\omega_* - \omega_0)\, R_0 \cos l - \omega_* d$



Longitudinal dependence

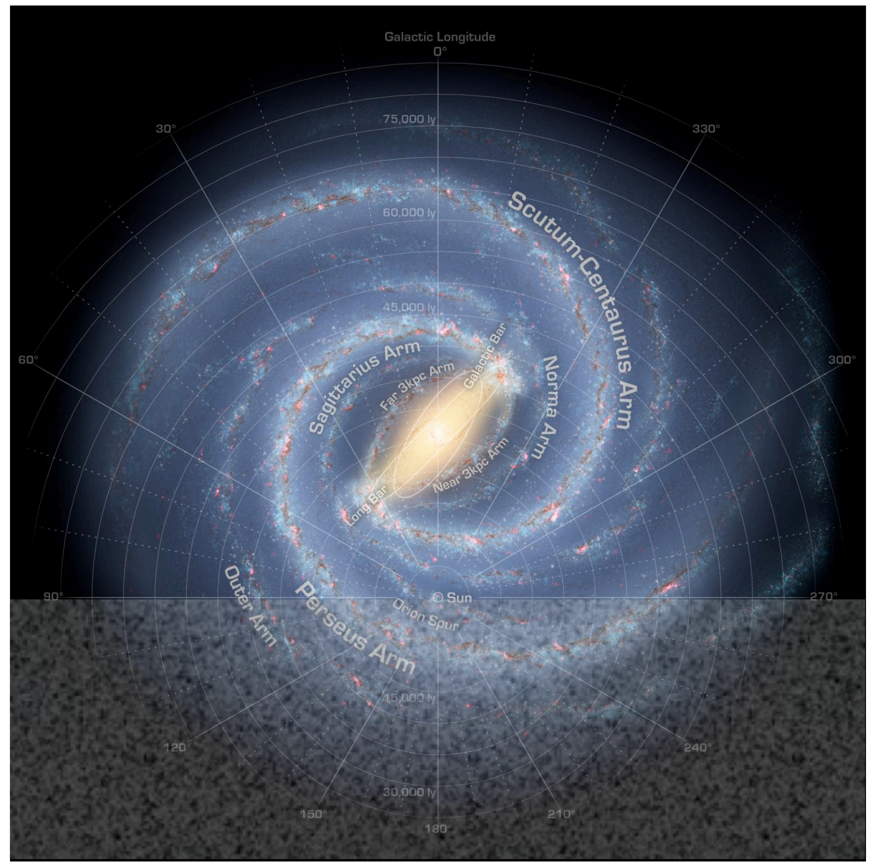
- $90^\circ \leq l \leq 180^\circ$
  - larger d
  - $R > R_0$
  - $\omega_*{}^* < \omega_0$
    - this means increasingly negative radial velocities
- $180^\circ \leq l \leq 270^\circ$
  - V_R is positive and increases with d



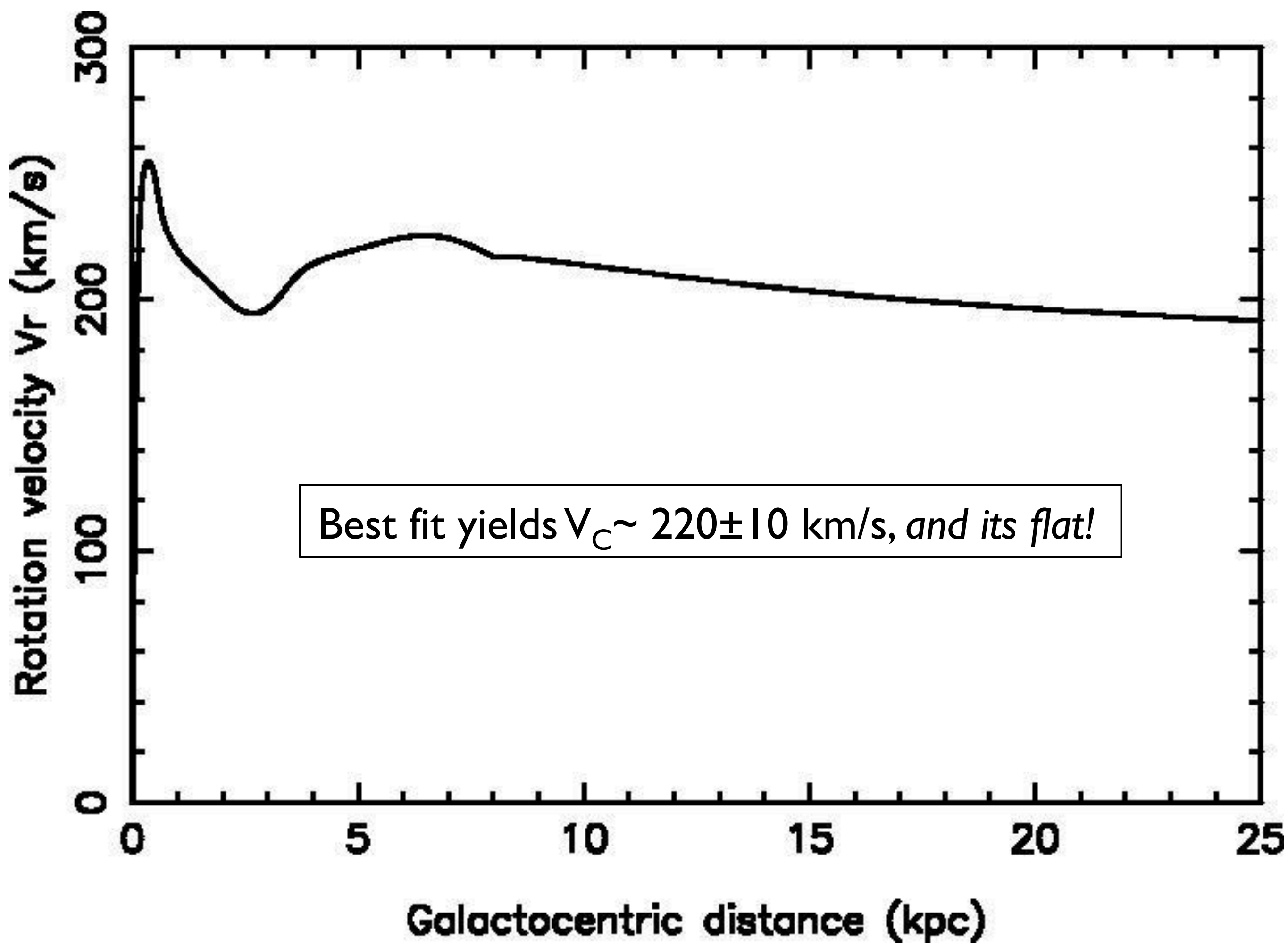
$90^\circ \leq l \leq 180^\circ$ $180^\circ \leq l \leq 270$

Longitudinal dependence

- $0° \leq l \leq 90°$
  - starting with small R, large ω
    - At some point $R = R_0 \sin(l)$ and $d = R_0 \cos(l)$
    - Here, V_R is a maximum ➔ tangent point.
    - *We can derive $\omega_*(R)$ and thus the Galactic Rotation Curve!*
- Breaks down at $l < 20°$ (why?) and $l > 75°$ (why?), but it's pretty good between 4-9 kpc from Galactic center.



Galactic Rotation Curve



Nakanishi & Sofue (2003, PASJ, 55,191)

Oort's Constant A: Disk Shear

- Assume d is small
  - this is accurate enough for the solar neighborhood
- Expand $(\omega_{*}-\omega_{0}) = (d\omega/dR)_{R0}(R-R_0)$
- Do some algebra….
  - $V_R = [(dV/dR)_{R0} - (V_0/R_0)]\ (R-R_0) \sin l$
- If $d << R_0$,
  - $(R_0-R) \sim d \cos(l)$
  - $V_R = A\ d \sin(2l)$
- where $A = ½[(V_0/R_0) - (dV/dR)_{R0}]$
  - This is the 1st Oort constant, and it measures the shear (deviation from rigid rotation) in the Galactic disk.

Oort's Constant B: Local Vorticity

- Do similar trick with the transverse velocity:
  - V_T= d [A cos(2l)+B], and
  - μ_l= [Acos(2l)+B]/4.74 = proper motion of nearby stars
- B = -12.4 ± 0.6 km/s/kpc
  - A measure of angular-momentum gradient in disk
- $\omega_0 = V_0/R_0$ = A-B
- $(dV/dR)_{R0}$= -(A+B)
- Observations of local kinematics can constrain the global form of the Galactic rotation curve