Astronomy 330
Class #6
18 September 2008
Review
- ISM detection techniques
- Chemical evolution

Stellar Luminosity Function

Star Counts and the Structure of the MWG

Does the MWG have a bar?
Review – Detecting the ISM

- Detection methods for ISM
  - CO → mm-wave
  - Hα → optical recombination line
  - Neutral ISM → 21 cm of HI

- Origin of the 21 cm line
  - Spin–flip, ν = 1.4204 GHz
  - \( I_\nu(\tau) = I_\nu(0)e^{-\tau} + S_\nu(1-e^{-\tau}) \), substitute \( T_B \) and \( T \) for \( I, S \)
  - \( N_H = 1.82 \times 10^{18} \int T_B \, dv \)

- Origin of the diffuse hot gas in galaxies
  - Likely from SNe
  - Hot gas is correlated with star formation/spiral arms in disk galaxies
What is the correlation between these observed absorption lines and the star formation history of this stellar system?
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
  - $\Delta M =$ change in mass

- $\Delta M_h = p \Delta M_s - Z \Delta M_s = (p-Z) \Delta M_s$
- $\Delta Z = \Delta(M_h/M_g) = [p \Delta M_s - Z(\Delta M_s + \Delta M_g)]/M_g$
- 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: $M_s(<Z(t))=M_g(0)[1-e^{-Z(t)/p}] \rightarrow$ we should see lots of really low metallicity G stars (something like 3% of G dwarfs should have z < 0.25$Z_0$)!
  - But we don’t (so-called G-dwarf problem)
Modeling the MWG

- What’s the stellar distribution?
Stellar Luminosity Function

- **Formalism**
  - $N(M,S) = \int \Phi(M,S)D(r)r^2dr$
    - $N =$ # of field stars of a given magnitude and spectral type
    - $\Phi =$ stellar luminosity function
    - $D(r) =$ density distribution

- **Malmquist Bias will get you...**
  - $\Phi(M,S) = \Phi_0/(2\pi)^{1/2}\sigma \exp(-(M-M_0)^2/2\sigma^2)$
  - $M_0 =$ mean magnitude
  - $\Phi_0 =$ # pc$^{-3}$ for some spectral type

- **We measure # of stars of some apparent magnitude, m.**
A(m) = \int \Phi(M) D(r) \omega r^2 dr

- \omega = \text{solid angle of survey}

What’s the mean magnitude of stars with apparent magnitude, m?

M(m) = \int M\Phi(M) D(r) r^2 dr / \int \Phi(M) D(r) r^2 dr

Move things around a bit....

- M(m) = M_0 - (\sigma^2 / A(m,S))(dA(m,S)/dm), and
- M_m - M_0 = -\sigma^2 \frac{d\ln A}{dm}

- 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
Stellar Luminosity Function

- Measure for a distance limited sample
- Bahcall & Soneira (1980) used:
  - \( \Phi(M) = \frac{n_\star 10^{\beta(M-M_\star)}}{[1 + 10^{-(\alpha-\beta)\delta(M-M_\star)}]^{1/\delta}} \)
    - \( n_\star = 4.03 \times 10^{-3} \)
    - \( M_\star = 1.28 \)
    - \( \alpha = 0.74, \beta = 0.04, 1/\delta = 3.40 \)
- See also Figure 2.4 in S&G.
- Basic results
  - \( 10^5 \) times more G stars than O stars
  - Nearby stars tend to be faint
  - Average \( M/L = 0.67 \, M_\odot/L_\odot \)
Zheng et al. 2004 601 500 (M dwarfs, I bnad)
M33 LF

Outer fields of M33 – Brooks et al. 2004 AJ 128 237
Star counts (z direction)

- \( n_z \) proportional to \( \exp(-z/z_0(m)) \), where \( z_0(m) \) is the scale height (and, yes, it does vary with magnitude)
- Reid & Majewski (1993)
  - Thin disk with \( z_0 = 325 \) pc
  - Thick disk with \( z_0 = 1200 \) pc
Du et al. 2003 A&A 407 541, stellar density perpendicular to the plane
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
HB stars in “the instability strip”
- Solar mass
- Opacity driven pulsations yield variability which is correlated with M
  \[ M = -2.3 \pm 0.2 \log(P) - 0.88 \pm 0.06 \] (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)
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:
  \( \exp(z/z_0)\exp(R/R_0) \)
Modeling the MWG

- We now know the stellar distribution.
- How big is the Milky Way?
Galactic Center

- Fascinating place, but we’ll concentrate on distance determination for now….
- RR Lyraes + other stellar tracers
  - Use the globular cluster population, OH/IR stars in the bulge
  - Get mean distances $\rightarrow$ 8.5 kpc
- Proper motion studies of Sgr A*
  - Look for maser emission
  - Follow maser proper motion + observed velocity $\rightarrow$ distance (7.5 kpc)
VLA 1.4 GHz view of G.C.

Lang et al. 1999
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Proper motion studies of Sgr A* 
- Look for maser emission
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But, wait, there’s more...

- 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?
  - $N = N_0 \exp(-0.5r^2)$, where $r^2 = (x^2+y^2)/R^2 + z^2/z_0^2$
  - Observe $I(l,b) = 1/4\pi \int N(x,y,z)ds$
  - Plug stuff from line (1) into this and you get something that looks bar-like.
Stellar kinematics – again use a population of easily identifiable stars whose velocity you can measure (e.g. OH/IR stars)

Sevenster (1990s) found overabundance of OH/IR stars in 1st quadrant. Asymmetry is also seen in RR Lyrae distribution

Gas kinematics: \( V_c = \left(\frac{4\pi G \rho}{3}\right)^{1/2} r \rightarrow \) we should see a straight line through the center (we don’t).
So far all we’ve dealt with is the distribution of stars. But, how do they move? We’ll get to the gory details later in the course, but for now let’s just look at a simple and useful 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 G.C. and the star is $l$, and the angle between the motion of the stars and the vector connecting the star and the Sun is $\alpha$. The Sun moves with velocity, $V_0$, and the other star moves with velocity, $V$. 
(1) Radial velocity of the star
- \( V_r = V \cos \alpha - V_0 \sin(l) \); now use law of sines to get...
- \( V_r = (\omega_* - \omega_0) R_0 \sin(l) \), where \( \omega \) is the angular velocity defined as \( V/R \).
- We can do the same thing with the transverse velocity....
Galactic Rotation

- \[ V_T = (\omega_* - \omega_0)R_0\cos(l) - \omega_*d \]
- \( l \) is something called the Galactic longitude
  - \( 90 \leq l \leq 180 \); larger \( d \), \( R > R_0 \), \( \omega_* < \omega_0 \), and this means increasingly negative radial velocities
  - \( 180 \leq l \leq 270 \); \( V_R \) is positive and increases with \( d \)
  - \( 0 \leq l \leq 90 \); starting with small \( R \), large \( \omega \)
    - At some point \( R = R_0\sin(l) \) and \( d = R_0\cos(l) \)
    - Here, \( V_R \) is a maximum \( \rightarrow \) 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

![Graph showing the rotation curve of the galaxy.](image)
Galactic Rotation Curve

- Best fit says $V_C \sim 220 \pm 10$ km/s, and its flat!!
- Now let’s zoom in on the local scale a bit more…
1. Assume \( d \) is small, this is accurate enough for the solar neighborhood
2. Expand \( (\omega_\ast - \omega_0) = (d\omega/dR)_{R_0}(R-R_0) \)
3. do some algebra….
4. \( V_R = [(dV/dR)_{R_0} - (V_0/R_0)](R-R_0)\sin(l) \)
5. If \( d \ll R_0 \), \( (R_0-R) \sim d \cos(l) \), and
6. \( V_R = Ad\sin(2l) \), where \( A = \frac{1}{2}[(V_0/R_0) - (dV/dR)_{R_0}] \); This is the 1\textsuperscript{st} Oort constant, and it measures the shear in the Galactic disk.
Oort’s Constants cont’d

- Do similar trick with the transverse velocity:
  - $V_T = d(A \cos(2l) + B)$, and
  - $\mu_1 = (A \cos(2l) + B)/4.74 = $ proper motion of nearby stars
- $\omega_0 = V_0/R_0 = A - B$
- $(dV/dR)_{R_0} = -(A + B)$
- Observations of local kinematics can constrain the global form of the Galactic rotation curve