Lecture 1:
Basic Model of the Milky Way, Galaxies
The Basics of Basics

Assumed that you are all familiar with these terms:

• effective temperature, spectral class

• distance modulus, absolute magnitude, bolometric luminosity

• HR diagram

• white dwarfs, horizontal branch, red giants, supergiants, subgiants, subdwarfs

• galactic coordinates
The Basic Milky Way Model

- **Disk(s):** population I, exponential (?) disks, thin and thick, rotating, lots of gas and dust, star-forming, spiral arms, bar

- **Spheroid (nucleus, bulge, halo):** population II, out to $\sim 100$ kpc, roughly a power-law, made of stars (different metallicity and kinematics than disk stars), globular clusters, no evidence for gas and dust

- **Is there structure in the outer halo?** Monolithic collapse (Eggen, Lynden-Bell & Sandage 1962) vs. merger scenario (Searle & Zinn 1978)
The Milky Way Kinematics

- There are three velocity components; ideally, we’d like to know their distributions as a function of the position in the Galaxy (to the first order, the disk rotates and the halo doesn’t)
- Standard description: Schwarzschild’s velocity ellipsoid (Gaussian distributions)
- Solar peculiar motion, the local standard of rest, asymmetric drift
- Circular-speed curve: \( v_c(R|z=0); v_c(R_\odot \sim 8.5 \text{ kpc}) = 220 \pm 15 \text{ km/s} \)
- Oort’s constants: measure \( v_c(R_\odot) \) and \( (dv_c/dR)|_{R=R_\odot} \)
9 epochs, unresolved, $n=216830$, psf mags, area=60 deg$^2$
Stellar Counts

There is a lot of information about the Milky Way structure (and stellar initial mass function, and stellar evolution) in SDSS imaging data.

How can we extract and interpret this information? What is the meaning of local maxima in the differential counts for some (but not all) color cuts?
Computing Differential Stellar Counts $n(m)$

1. $n(m) = dN/dm = dN/dV \frac{dV}{dm}$,
   \[ dN/dV = \rho(l, b, D) \text{ (}\rho\text{ constrains Galactic Model)} \]

2. For a pencil beam: $dV = \Delta\Omega D^2 dD$

3. $D = 10 \text{pc} 10^{0.2(m-M)}$, $dD/dm = 0.2 \ln(10) D(m)$

4. $n(m) = \rho(l, b, m) 0.2 \Delta\Omega \ln(10) (10 \text{ pc})^3 10^{-0.6M} 10^{0.6m}$

\[ n(m) \propto \rho(l, b, m) 10^{0.6m} \]
Examples for $n(m) \propto \rho(l, b, m) 10^{0.6m}$

- **Power-law:** $\rho(l, b, D) \propto D^{-n}$

  $$n(m) \propto 10^{km}, \quad k = 0.6 - 0.2n$$

  - Euclidian counts ($n=0$): $n(m) \propto 10^{0.6m},$
  - Halo counts ($n=3$): $n(m) = \text{const.}$

- **Exponential disk:** $\rho(l, b, D) \propto e^{-D/H}$

  at a distance $D = kH$, $n(m)$ has a local slope corresponding to a power-law with $n = k$. Hence, for $D = 3H$, the differential counts for exponential density distribution have a local maximum!
9 epochs, unresolved, n=216830, psf mags, area=60 deg$^2$
$M_i = f(g-i)$

- --- Hawley et al. (2002)
- --- Siegel et al. (2002)
- --- Golimowski et al. (2002)
What are SDSS counts telling us?

- For $g - r \sim 0.5$, maximum for $n(m)$ at $r = 17$
  
  $g - r \sim 0.5$ implies $g - i \sim 0.8$ and $M_r \sim 5.7$: $H' \sim 1800 \text{kpc}$

- For $r - i \sim 1.5$, maximum for $n(m)$ at $r = 21.5$
  
  $r - i \sim 1.5$ implies $g - i \sim 2.9$ and $M_r \sim 12$: $H' \sim 800 \text{kpc}$

- $H' = H/\sin b \sim 2H$, in agreement with expectations for thin ($H \sim 300 \text{pc}$) and thick ($H \sim 1.0 \text{kpc}$) disks.

- With SDSS we can do better than with this standard approach because the vast majority ($\sim 98 - 99\%$) of detected stars are on the main sequence and the photometry is very accurate.
Dissecting Milky Way with SDSS

- Standard approach: assume initial mass function, fold with models for stellar evolution; assume mass-luminosity relation; assume some parametrization for the number density distribution; vary (numerous) free parameters until the observed and model counts agree. **Uniqueness? Validity of all assumptions?**
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• The vast majority of stars detected by SDSS are on the main sequence: *stars in a narrow color bin all have about the same luminosity*, and this luminosity can be estimated from photometric parallax relation.
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- Since the distance to each star is known, its 3-dimensional position ($X, Y, Z$, or $R, z, \phi$) in the Galaxy is known: **direct determination of the stellar number density**
SDSS stars with $1.0 < r-i < 1.1$ ($-9.1 < \ln(\rho) < -5.2$)

Model: $\ln(\rho) = -5.46$, $Z_g = 28$ pc, $H = 295$ pc, $L = 3.0$ kpc
To Boldly Go Where None Has Gone Before

- **Photometric parallax** works for distances from $\sim 100$ pc to $\sim 10$ kpc. Can we see further out, say to $\sim 100$ kpc?

- Distance modulus for 100 kpc is 20 mag – to have an apparent magnitude $m < 21$, a star must have $M < 1$.

- Horizontal branch stars (including RR Lyrae) and red giants are good tracers of the outer halo

- **Selection:** RR Lyrae stars: variability, color, spectroscopic selection (?); Horizontal branch stars: color, spectroscopic selection; red giants: color, spectroscopic selection (?)
Green dot: Seattle. Red dots: ~ 3,000 SDSS RR Lyrae candidates.
Galactic Distribution of 3,127 SDSS candidates RR Lyrae
Monoceros “ring” (Yanny et al. 2003)
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- consistent with a tidal stream slightly inclined wrt Galactic plane

- confirmed by 2MASS data (Rocha-Pinto et al. 2003, Crane et al. 2003)
Pal 5 tidal tails (Rockosi et al. 2002, Odenkirchen et al. 2003)
Pal 5 tidal tails: matched filter extraction, gray: SFD E(B-V)
Milky Way Kinematics (with SDSS)

- Kinematics (e.g. proper motions) are a complex function of color and apparent magnitude
- SDSS enables three important advances (accurate distances, radial velocities and proper motions) which results in robust and accurate estimates of all three velocity components
- Data confirm a strong correlation between the kinematics and metallicity (with a 100-1000 large sample than previous studies)
Milky Way Kinematics (with SDSS)

- Both the rotational velocity and the dispersion for all three components appear independent of $Z$ for low-metallicity ($u - g < 1$) stars
- Both the rotational velocity and the dispersion for all three components increase with $Z$ for high-metallicity ($u - g > 1$) stars
- More details in Bond et al. (2005)
Galaxies (in SDSS)

- Galaxies are (mostly) made of stars (also gas, dust, AGN); hence have similar (but not identical) color distributions
- They come in various shapes (spiral vs. ellipticals; exponential vs. de Vaucouleurs profiles, SDSS concentration parameter)
- Luminosity functions, mass distribution functions, ages, metallicity
- Some host AGNs, some have high star-formation rates
- Nearest neighbors: the Andromeda galaxy (M31), Large and Small Magellanic Clouds, the Sgr Dwarf, Mon stream progenitor (?), the Virgo overdensity (?)
SDSS Spectroscopic Galaxy Survey

- **Two samples:** the “main” galaxy sample ($r_{Pet} < 17.77$, Strauss et al. 2002), and luminous red galaxy sample (LRG, cut in color-magnitude space, Eisenstein et al. 2002)

- Distance estimate allows the determination of luminosity function (Blanton et al. 2001)
Bi-modal Color Distribution

- Strateva et al. (2001): galaxies have bi-modal $u - r$ color distribution
- Colors correlated with shapes and profiles (SDSS concentration parameter)
- Sersic index $n$:
  \[ I(R) \propto \exp\left(-\left(R/R_e\right)^{1/n}\right) \]
  - $n = 1$: exponential profile
  - $n = 4$: de Vaucouleurs profile
- Blanton et al. (2003), Smolčiç et al. (2004): “everything is correlated with everything”
- Schechter function:
  \[ \Phi(L)dL \propto (L/L_*)^\alpha \exp(-L/L_*) \frac{dL}{L} \]
• Spectra are correlated with morphology

• Principal component analysis: spectra form a low-dimensional family: it is possible to describe most of variance using only 2 parameters (Yip et al. 2004)

• Both AGNs and star-forming galaxies show emission lines: How do we separate AGNs from star-forming galaxies?