Astronomy 540:
Components of Galaxies: Disks, Bulges,
Interstellar Medium, Kinematic properties

Milky Way Schematic from Freeman and Bland-Hawthorn 2002

MW Bar from 2μm data, Blitz & Spergel 1991
MW Structure
as given in Drimmel & Spergel 2001

Dust

Stars at 2.2μm

8kpc
These flux normalizations correspond to J-K=0.6. Too blue?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk:</td>
<td></td>
<td></td>
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<tr>
<td>Normalization in J</td>
<td>$\eta_J^0$</td>
<td>14.7 MJy sr$^{-1}$ kpc$^{-1}$</td>
<td>2.3 (4.2)</td>
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<tr>
<td>Normalization in K</td>
<td>$\eta_K^0$</td>
<td>11.6 MJy sr$^{-1}$ kpc$^{-1}$</td>
<td>1.7 (3.2)</td>
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<tr>
<td>Radial scale length</td>
<td>$r_*$</td>
<td>2.264 kpc</td>
<td>0.083 (0.19)</td>
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<tr>
<td>Scale height</td>
<td>$h_*$</td>
<td>282.2 pc</td>
<td>7.9 (20.)</td>
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<tr>
<td>Cutoff radius</td>
<td>$r_c$</td>
<td>10.52 kpc</td>
<td>0.34</td>
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<td>Spiral arms:</td>
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<tr>
<td>Amplitude in J</td>
<td>$B_J$</td>
<td>0.86</td>
<td>0.25</td>
</tr>
<tr>
<td>Amplitude in K</td>
<td>$B_K$</td>
<td>1.28</td>
<td>0.24</td>
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<tr>
<td>Mean age in J</td>
<td>$\tau_J$</td>
<td>5.5 Myr</td>
<td>3.6</td>
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<tr>
<td>Mean age in K</td>
<td>$\tau_K$</td>
<td>17.6 Myr</td>
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<td>Arm width coefficient J</td>
<td>$c_J^*$</td>
<td>142 pc kpc$^{-1}$</td>
<td>43.</td>
</tr>
<tr>
<td>Arm width coefficient K</td>
<td>$c_K^*$</td>
<td>143 pc kpc$^{-1}$</td>
<td>69.</td>
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<td>Corotation radius</td>
<td>$i$</td>
<td>6.66 kpc</td>
<td>0.39</td>
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<td>Dust:</td>
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<tr>
<td>$V$ opacity</td>
<td>$\kappa_V$</td>
<td>0.0180 (MJy sr$^{-1}$)$^{-1}$</td>
<td>0.0029</td>
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<tr>
<td>Emissivities</td>
<td>$k_+$</td>
<td>3.98</td>
<td>0.35 (0.45)</td>
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<tr>
<td></td>
<td>$k_-$</td>
<td>1.29</td>
<td>0.10 (0.26)</td>
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<tr>
<td></td>
<td>$k_a$</td>
<td>2.07</td>
<td>0.37 (2.9)</td>
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<td>Densities</td>
<td>$\rho_s$</td>
<td>121. MJy sr$^{-1}$ kpc$^{-1}$</td>
<td>23. (32.)</td>
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<tr>
<td></td>
<td>$\rho_a$</td>
<td>61. MJy sr$^{-1}$ kpc$^{-1}$</td>
<td>16. (26.)</td>
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<td>Miscellaneous:</td>
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<td></td>
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<tr>
<td>Height of Sun</td>
<td>$Z_\odot$</td>
<td>14.6 pc</td>
<td>2.3</td>
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<td>Warp coefficient</td>
<td>$a_w$</td>
<td>27.4 pc kpc$^{-2}$</td>
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<td>J offset</td>
<td>$Q_J$</td>
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<td>0.0082</td>
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<tr>
<td>K offset</td>
<td>$Q_K$</td>
<td>-0.0744 MJy sr$^{-1}$</td>
<td>0.0069</td>
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</table>
Surface Brightness Profiles for Other Spirals


The Galactic Bulge and Halo
Photometric Structure

Motivation
-
- unlike more familiar dynamical systems (e.g., solar system, stellar systems), the orbital properties of stars in galaxies reflect not just Newtonian dynamics, but also the mass distribution and dynamical history of the galaxy

- consider basic dynamical timescales for Milky Way
  - crossing time \( \tau_{\text{cross}} \sim \frac{2R}{v_{\text{orbit}}} \sim 10^8 \text{ years} \)
  - relaxation time \( \tau_{r} \sim \tau_{\text{cross}} N^{1/2} \sim 10^{14} - 10^{15} \text{ years} \)

(!)
- implication: galaxies have dynamical memories!
  - present structure reflects dynamical history over \( >10 \) Gyr
Structure of Galactic Spheroids

- **Radial structure**
  - if we approximate spheroids as relaxed, purely stellar systems, stellar dynamical theory provides a semi-empirical description (King 1962, AJ, 67, 471)
    - isothermal core, with projected brightness
      \[
      I(r) = I_0 / (1 + r/r_c)^2 \quad r_c \rightarrow \text{core radius}
      \]
    - King model also requires outer truncation, parametrized by a tidal radius
      \[
      c = \log (r_t / r_c)
      \]

King was also trying to fit globular clusters when he developed this model, and the outer truncation made sense for them.

King 1966, AJ, 71, 64
King profile fit to NGC 4472 - very similar to spiral bulge

Spiral Galaxies

**Bulges**
- luminosity profiles are well fitted by a $r^{1/4}$ law
- structure similar to elliptical galaxies, with typically higher flattening

**Disks (radial structure)**
- most disks well fitted with an exponential profile:
  \[ I(r) = I_0 e^{-r/h} \]  
- For normal spirals central surface brightnesses ($I_0$) distribute around typical values $\mu_B = 21 - 22$ mag/sq arcsec. However prominent exceptions exist in either extreme
  - $\mu_B \ll 21$ "pseudo-bulges"
  - $\mu_B \gg 22$ low surface brightness galaxies "(LSBs)"

- scale lengths $h$
  - typically 1 - 5 kpc
  - much smaller/larger in pseudo-bulges/LSBs
  - wavelength dependent, reflecting radial trends in color (metal abundance and/or age)
• Typical radial profiles

The volume corrected bivariate distribution of galaxies in the $(\mu_0, M)$-plane. The number density $\delta(\mu_0, M)$ is per bin size, which is in steps of 1 mag in $M$ and 1 mag arcsec$^{-2}$ in $\mu_0$. 

Fig. 23.
• Bulge/disk properties
  - B/D ratio correlates with galaxy type (as expected!), but with a large dispersion
  - Interpretation: SFR, arm structure, etc only loosely correlated with spheroid/disk fraction
• Disks: vertical structure
  - several photometric studies of external galaxies, classic study
  - vertical light profiles well fitted by sech function:
    \[
    \rho(z) = \rho_0 \text{sech}^2 \left( \frac{z}{z'} \right) \quad \text{[sech } z = \frac{2}{e^z + e^{-z}}\text{]}
    \]
    (for large z this is exponential with scale height \(z_0 = z'/2\))
  - disks well fitted with typical scale length \(z_0 \sim 300\) pc
  - stellar scale height is roughly constant with radius, despite exponential falloff in disk surface density
  - most disks show sharp outer edges
  - some evidence for second (thick) disk components, with \(z_0 \sim 1\) kpc
    • but presence and properties of thick disk appear to vary widely
    • thick disks more common in galaxies with massive bulges
• Bars and Associated Structures
  Buta et al 1996, Barred Galaxies, ASP Conf Ser, Vol 91

  - strong bars observed in ~1/3 of spirals, weak bars in ~1/3
  - fraction of total luminosity in bar typically 10-30%
  - isophotes typically “boxy”, profiles can be fitted by power laws or exponential functions
  - inner, outer rings closely associated with presence of bar
  - some bars contain bulges or bars within bars
  - bars rotate in rigid pattern with pattern (precession) speed co-rotating with disk at end of bar (density wave)
    [corotation radius = radius at which a star on a circular orbit moves at the same angular freq. as the bar’s pattern]
  - bars appear to fall into two distinct classes, “strong” and “weak”
Interstellar Media

• An entire other course (Astr 515), here we focus on large-scale structure and global physical properties

• Overview: the Galactic ISM

<table>
<thead>
<tr>
<th>Component</th>
<th>$f_{vol}$</th>
<th>$&lt;n_H&gt;$</th>
<th>$T_e$</th>
<th>$f_M$</th>
<th>Probes</th>
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<tbody>
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<td>Hot ICM</td>
<td>0.5</td>
<td>0.005</td>
<td>500,000</td>
<td>0.001</td>
<td>X-rays, OVI</td>
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<tr>
<td>WIM</td>
<td>0.5</td>
<td>0.3</td>
<td>8,000</td>
<td>0.05</td>
<td>Ha, IS abs lines</td>
</tr>
<tr>
<td>Warm HI</td>
<td>0.05:</td>
<td>1:</td>
<td>8,000</td>
<td>0.05</td>
<td>HI, IS abs lines</td>
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<tr>
<td>HI Clouds</td>
<td>0.05</td>
<td>5-20</td>
<td>10-100</td>
<td>0.4</td>
<td>HI 21cm line</td>
</tr>
<tr>
<td>H$_2$ Clouds</td>
<td>0.005</td>
<td>&gt;100</td>
<td>5-30</td>
<td>0.5</td>
<td>CO, HCN, (H$_2$)</td>
</tr>
<tr>
<td>HII Regions</td>
<td>0.001</td>
<td>10-10000</td>
<td>10,000</td>
<td>0.02</td>
<td>Ha, radio cont</td>
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<tr>
<td>Dust</td>
<td>1.0</td>
<td>5-60</td>
<td>0.01</td>
<td></td>
<td>IR, extinction</td>
</tr>
<tr>
<td>Particles/Fields</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td>radio cont, $\gamma$-rays</td>
</tr>
</tbody>
</table>
Atomic Gas

- Most information comes from measurements of 21 cm HI line
  - single-dish measurements of several thousand galaxies
    - integrated HI flux --> HI masses
    - integrated line profiles --> radial velocities, rotation velocities
  - aperture synthesis mapping
    - detailed HI distributions
    - rotation curves, detailed 2D velocity fields
    - (nearby galaxies) cloud/inter-cloud structure of atomic ISM, temperature distributions
HI Distribution

- gas is much more extended --> typically $R_{\text{HI}} \sim 1.5-5 \ R_{25}$
  - star formation has proceeded over only part of the disk
  - HI kinematics can be used to trace the gravitational potential at large radii (tens of kpc)
M81 group: VLA

HI Kinematics

• Usually most HI rotates at roughly constant velocity ("flat rotation curve")
  - integrated HI line profile has characteristic "double-horned" shape
  - provides precise measurements of radial velocity and linewidth
Trends with Galaxy Type: HI

- HI comprises ~half of total gas mass in typical spiral (vs ~50% H$_2$)
- HI gas fraction strong function of Hubble type
- $M_{HI}/M_{HI+stars}$ ranges from 0.0 to 0.9 from types E to Irr

Roberts & Haynes 1994, ARAA, 32, 115
Molecular Gas

- Most molecular gas is in form of $\text{H}_2$, but cold $\text{H}_2$ gas has no easily observable emission lines (fundamental at $28 \mu \text{m} \sim 180 \text{K}$).
  - most information comes from millimeter rotational transitions of CO molecule, with supplemental information from CO isotopic lines and other molecules (HCN, OH...)
  - primary CO transition at 2.7 mm ($J = 1 \rightarrow 0$)
  - again, data on external galaxies come from a combination of single-disk and aperture synthesis measurements

- $\text{H}_2$ predominantly found in massive cold clouds ($10^4 M_\odot$ and up), highly optically thick in CO mm transitions
  - mass of $\text{H}_2$ inferred empirically from correlation with CO brightness temperature (intensity) \textit{controversial subject!}
    \[ N(\text{H}_2) \ (\text{cm}^{-2}) \sim 3 \times 10^{20} \ I(\text{CO}) \ (\text{K km s}^{-1}) \]
**CO Distribution**

- In spiral galaxies, CO tends to follow the distribution of stars more closely, especially young stars.
  - Little/no CO beyond the optical radius.
- In many low-mass galaxies (S, Irr), CO is systematically weak compared to young stars and HI.
  - May reflect breakdown of CO/H$_2$ conversion factor and change in molecular cloud properties.

BIMA SONG Survey


Trends with Galaxy Type: $^4$CO

- Molecular gas tends to be dominant phase in early-type spirals, with $H_2$ fraction decreasing in later type, lower luminosity galaxies
- role of physical trends vs changes in $CO/H_2$ factor uncertain
- strong increase in total gas fraction (atomic + molecular) with type

Young & Scoville 1991, ARAA, 29, 581
Young & Scoville 1991, ARAA, 29, 581
Interstellar Dust

• Approximately 1% of ISM is in form of solid grains, which tie up ~50% of heavy elements in ISM
• Grains typically absorb ~40% of bolometric energy of galaxies in local universe
  - can study via modeling of extinction in visible, UV (difficult!)
  - dust grains re-emit energy in mid-far infrared (5 - 300 µm), can map structure directly

• Milestones
  - 1930: Trumpler shows that extinction and reddening are correlated
  - <1983: extinction modeling, fragmentary FIR data
  - 1983: IRAS all-sky survey, total fluxes of 14,000 galaxies at 12, 25, 60, 100 µm
  - 1995: ISO mission, maps of galaxies at 7, 15 µm, low-res mapping to 240 µm
  - 2003: Spitzer mission, maps at 3.5 - 160 µm, spectral maps
Dust Emission

• Integrated spectrum of our Galaxy (below) is characteristic of galaxies generally
  - dust emission much broader than single temperature component, but can be fitted with ~4 distinct components
    • $T \sim 15 \text{ K} \ (100 - 300 \ \mu\text{m})$ cold dust in molecular clouds
    • $T \sim 20-30\text{K} \ (100-150 \ \mu\text{m})$ dust in diffuse clouds, “IR cirrus”
    • $T \sim 60 \text{K} \ (50 \ \mu\text{m})$ warm grains in star forming regions
    • $T \sim 300 \text{K} \ (10 \ \mu\text{m})$ PAH band emission in small grains
      (PAH = polycyclic aromatic hydrocarbon)

• IR morphology traces optical dust lanes, star-forming regions

• Strong trend in relative emission with type

NGC 6946

Hα

ISO 15 µm


Warm Ionized ISM

• HII regions
  - directly trace massive star formation
  - primarily traced by hydrogen recombination lines
    \((\text{H}\alpha, \text{P}\alpha, \text{Br}\gamma)\) or thermal radio continuum

• Diffuse ionized gas
  - characteristic density 0.01 - 0.1 cm\(^{-3}\)
  - in spiral galaxies gas is primarily photoionized by UV radiation escaping HII regions
    • early-type galaxies (spheroids) may possess completely diffuse phase, that is primarily heated by shocks
  - in some galaxies (e.g., NGC 891) medium comprises significant fraction of ISM mass, energy budget
  - sometimes associated with diffuse neutral phase
NGC 2841 Sb

NGC 3184 Sc

NGC 4449 Irr
Hot Ionized (Coronal) ISM

- Primarily traced via soft X-ray bremsstrahlung emission (1-10 keV) or high-ionization UV absorption lines (e.g. OVI)
- Characteristic $T \sim 3-5 \times 10^5$ K, $n \sim 10^{-3}$ cm$^{-3}$
  - high temperatures require kinetic heating (supernovae, stellar winds, cloud-cloud collisions)
- Several types of structures
  - diffuse coronae in/around massive E/S0 galaxies, bulges
  - diffuse disk emission from supernova remnants, stellar wind bubbles, supershells
  - extraplanar fountains, chimneys, “superwinds”
  - infalling clouds, cooling flows
**CXO Images**

http://www.chandra.harvard.edu

**NGC 4649 = M60** E2  
Randall & Sarazin 2001, unpub

**NGC 4631: Sc**  
NGC 1569
Irr

Relativistic Particles, Fields

- Radio continuum emission of galaxies at cm wavelengths is primarily non-thermal synchrotron radiation, from relativistic electrons in the Galactic magnetic field
  - thus radio emission (distribution, polarization) traces high-energy processes and structure/strength of interstellar magnetic field
  - B field probably plays critical role in large-scale structure of ISM, and possibly in Galactic evolution, but poorly understood
  - B fields also traced via Zeeman measurements, optical/UV polarization of starlight (via grain alignment)
Figure 4. Polarized radio emission and B-vectors of the spiral galaxy NGC 6946 at λ6 cm, combined from observations with the VLA and Effelsberg telescopes (from Beck et al., 1996) and overlaid onto an Hα image of Ferguson et al. (1998). The angular resolution of the radio image is 15 arc sec.
Internal Kinematics

Motivation

- determine masses and mass distributions of galaxies
- measure extent and distribution of dark matter
  - extended dark matter inside galaxies and in halos
  - central massive black holes
- kinematical and structural properties of galaxies are tightly coupled via fundamental planes
  - important clues to the physical nature of Hubble sequence
  - utilize scaling laws as extragalactic distance methods
- kinematics offer vital clues to the formation and dynamical evolution of galaxies
Disks

- Observational technique: disks are rotationally supported, so key diagnostic is gas-phase "rotation curve"

- optical emission lines (e.g., Hα, [NII])
- 21 cm HI line (large radii)
- CO mm line
- stellar absorption lines

Rotation Curves

- characteristic form is roughly linear increase in inner regions, with constant velocity ("flat rotation curve") in outer disk
- inner slope correlated with mass distribution (visible + dark)

Sofue & Rubin 2001, ARAA, 39, 137
Stellar vs gas rotation

- stellar absorption lines can also be used to measure rotation curve, but stellar velocities systematically lag the gas: “asymmetric drift”
- stars have systematically higher velocity dispersion, so circular component at given radius is lower


Dark matter

- Flat outer rotation curves imply ~linear increase in enclosed mass with radius, to R~ 40 kpc and beyond
  - implies increase in mass density as $1/r^2$ to $1/r$, depending on 3D distribution, whereas observed luminosity is declining exponentially
  - studies of satellite galaxies, binary galaxies, etc indicate linear mass increase to $>>100$ kpc, and enclosed masses $>>10^{12} \, M_\odot$

Figure 1  Mass of the Milky Way interior to radius $R$ determined from observations of globular clusters and dwarf spheroidal galaxies; all data have been averaged in radial bins. The vertical bars are the standard error of the mean of each bin. Filled dots are mass measurements from globular cluster tidal radii, stars refer to dynamical mass determinations, and open circles are masses derived from tidal radii of dwarf spheroidal galaxies.

Faber & Gallagher 1979, ARAA, 17, 135
Scaling laws

- rotation velocity of disks tightly correlated with total luminosity: “Tully-Fisher relation”

- \( L \propto v_c^4 \) (cf. Faber-Jackson relation for ellipticals/bulges)

- parametrized in terms of rotation speed or 21 cm linewidth

- slope and dispersion wavelength dependent, relation tightest in near-infrared

- used heavily as extragalactic distance indicator (distance scale, \( H_0 \), peculiar velocities)

\[ W = \text{width of 21cm line in km/sec} \]

Systematics along Hubble sequence

- infrared T-F relation insensitive to galaxy type or surface brightness
- slope of inner rotation curve steepest in early Hubble types, reflecting higher mass concentration in bulge
- $M/L_B$ ratios systematically lower in late-type disks, reflecting younger stellar populations
  - trends nearly absent in $M/L_K$
  - Tully-Fisher rotation velocity of disks tightly correlated with total luminosity: "Tully-Fisher relation"

Faber & Gallagher 1979, ARAA, 17, 135
stellar and gaseous velocity dispersions

- Disks in luminous (early-type) spirals tend to be “hot”, with $<\sigma_v> \sim 60-120$ km/sec
- Disks colder in less luminous, late-type galaxies
- $<\sigma_v>$ scales roughly with $v_c$, but relation not strictly linear
- Velocity dispersion decreases with radius
  - Explains observation of approx. constant disk thickness with radius
- Gas disk shows different behavior, with nearly constant $\sigma_v \sim 6-10$ km/sec

• **kinematic peculiarities**
  - systematic deviations from normal rotation present around bars and in spiral arms, due to non-axisymmetric mass distribution
  - approximately 20-40% of disks show abnormalities in the stellar or gas velocity fields
    - asymmetric rotation curves
    - non-circular motions, streaming in outer disks (e.g., interactions)
    - counter-rotating disks
    - orthogonal disks (polar rings)
  - frequency of peculiarities higher in compact groups, rich clusters
NGC 4550
star-star counter-rotation

NGC 4826
gas-gas counter-rotation
gas-star counter-rotation
