Kinematics of Galaxies

- Spectral Features of Galaxies
- Basics of Spectroscopy
- Elliptical Kinematics
- Faber-Jackson and the Fundamental Plane
- Disk Kinematics (Stellar and H I)
- 2D Velocity Fields
- Rotation Curves and Masses
- Tully-Fisher
- Detection of Supermassive Black Holes
Stellar Spectra

(Sparke and Gallagher, p. 5)
Galaxy Spectra - Ellipticals

(Sparke and Gallagher, p. 267)

- Most features from giant G and K stars (e.g., G band is from CH)
- In the optical, most absorption is stellar. Ca II H, K and Na I D can come from ISM as well (but not much in Ellipticals)
- Lines are broadened from stellar motions
- Ca II triplet lines at ~8500 Å are good for kinematics (well separated, uncontaminated)
Disk Galaxies

- SO similar to E’s $\rightarrow$ old stellar populations
- Sa/Sb have stronger Balmer lines (A, F stars) and bluer continua
- Sc have emission lines from H II regions (young hot stars)
- Starburst galaxies have very strong emission lines and blue continua

(Sparke and Gallagher, p. 224)
1. Continuum Flux: \[ F_c = \frac{\int F_\lambda \, d\lambda}{\Delta \lambda} = \langle F_\lambda \rangle \] (ergs s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\))

2. Emission Line Flux: \[ F = \int (F_\lambda - F_c) \, d\lambda \] (ergs s\(^{-1}\) cm\(^{-2}\))

3a. Absorption Equivalent Width: \[ W_\lambda = \int (1 - F_\lambda / F_c) \, d\lambda \] (Å)
3b. Absorption-Line Centroid:
\[
\lambda_c = \frac{\int \lambda (F_c - F_\lambda) d\lambda}{\int (F_c - F_\lambda) d\lambda}
\]  (Å)

3c. Radial Velocity Centroid:
(nonrelativistic)
\[
v_r = \frac{\lambda_c - \lambda_{lab}}{\lambda_{lab}} c
\]  (km s\(^{-1}\))
• For Galactic kinematics, $v_r$ and $\sigma$ are used
• A **Gaussian** profile is often assumed for the LOSVD (line of sight velocity distribution):

\[
P(v_r) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(v_r/\sigma)^2}
\]

where $v_r = \text{centroid} = \text{peak}$, $\sigma = \text{velocity dispersion}$
• Note the full-width at half-maximum for a Gaussian is:

\[\text{FWHM} = 2.355 \sigma\]
Spatially-Resolved Spectra

- Long-slit spectroscopy: spectra at each position along slit
- Resolving power needed: $R = \frac{\lambda}{\Delta \lambda} \approx 5000$
  (where $\Delta \lambda$ is the FWHM of the line-spread function (LSF)
- Measure $v_r$ and $\sigma$ at each position.
- Subtract *systemic* velocity (due to Hubble flow, etc.) from $v_r$
- Net $v_r$ at each position is a measure of rotation: $v_r = v \sin (\text{incl})$
- $\sigma$ gives component of random motion in the line of sight
Ellipticals: Kinematics

Ex) cD galaxy NGC 1399

(Sparke and Gallagher, p. 257)

- For most E’s: \( v_r \) (max) \(<<\) \( \sigma \) (central velocity dispersion)
Determination of $v_r$ and $\sigma$

- One method: use cross-correlation function (CCF)
- Cross-correlate the galaxy spectrum with that of a star (like a K giant) or a synthetic galaxy
  - At each $\lambda$, you have $F_\lambda(\text{star})$ and $F_\lambda(\text{galaxy})$
  - Do a linear fit of $F_\lambda(\text{galaxy})$ vs. $F_\lambda(\text{star})$ to get “r”
    (linear-correlation coefficient) (Bevington, p. 121)
  - Shift one spectrum in $\lambda$, and calculate r again
    ($r = 1 \Rightarrow$ perfect correlation; $r = 0 \Rightarrow$ no correlation)
  - The CCF is just r as a function of shift
- The CCF peak give the velocity centroid $v_r$; the CCF width gives $\sigma$
- The auto-correlation function (ACF) is a function cross-correlated with itself.
CCF Example

- K0 giant
- NGC 2549

(Binney & Merrifield p.695, 698)
Results for Ellipticals: Kinematic Correlations

- Faber-Jackson relation: \( L \sim \sigma^4 \) (\( \sigma \): central velocity disp.)
  \[
  \frac{L_V}{2 \times 10^{10} L_\odot} = \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^4
  \]

- Note \( L \sim I_e R_e^2 \) → Is there a tighter relationship for \( \sigma, I_e, R_e \)?

→ projection:

\[
I_e^{1.64} R_e^2 \propto \sigma^{2.48}
\]

Note: These relations do not apply to diffuse E’s and dwarf spheroidals

(Sparke and Gallagher, p. 258)
Rotation of Elliptical Galaxies

• **Is the oblateness of ellipticals due to rotation?**
  → no, E’s tend to rotate more slowly than they should

• **How fast should they rotate?**

• **Virial Theorem** – if the galaxy is dynamically relaxed, velocity dispersions are equal in all directions and:

  \[2\langle KE_i \rangle + \langle PE_i \rangle = 0\]
  for \(i = x, y, z\) (axes of symmetry)

  where \(\langle PE_i \rangle\) is the average gravitational potential.

  For an oblate galaxy rotating around the z axis:

  \[
  \frac{\langle PE_z \rangle}{\langle PE_x \rangle} = \frac{\langle KE_z \rangle}{\langle KE_x \rangle} = \frac{\sigma_z^2}{\frac{1}{2} v^2 + \sigma_x^2}
  \]

  \[
  \frac{\langle PE_z \rangle}{\langle PE_x \rangle} \approx (B / A)^{0.9} = (1 - e)^{0.9} \quad \text{(Sparke & Gallagher, 260)}
  \]

  where A, B, and e are the actual axes and ellipticity
If the virial theorem applies, \( \sigma = \sigma_x = \sigma_y = \sigma_z \).

Note that the maximum radial velocity at \( \sigma \) (\( = \sigma_0 \)) is:

\[
v(\text{max}) \approx \frac{\pi}{4} v \quad \text{(Sparke & Gallagher, p. 260)}
\]

Thus

\[
\frac{v(\text{max})}{\sigma} = \frac{\pi}{4} \sqrt{2 \left[ (1 - e)^{-0.9} - 1 \right]}
\]

\( \rightarrow \text{observed } v(\text{max}) \text{ much lower than expected from relaxed systems} \)
• So most ellipticals are not supported by rotation, but by anisotropic velocity dispersions: $\sigma_x \neq \sigma_y \neq \sigma_z$.

Observations: Let $(v/\sigma)_* = \frac{(v_{\text{max}}/\sigma_0)_{\text{obs}}}{(v_{\text{max}}/\sigma_0)_{\text{eqn}}}$

(Sparke & Gallagher, p. 261)

• Luminous and boxy ellipticals rotate much slower than expected.
• Disky E’s may be composite: rotating disk embedded in normal elliptical
Kinematics of Rotating Disks (Spirals)

- Spiral galaxies are dominated by rotation ($v_r \geq 10\sigma$)
- Can determine true velocity $v(R)$, since we know inclination

![Diagram showing the relationship between edge-on and inclined views of a rotating disk, with the observed radial velocity given by $v_r = v_{\text{sys}} + v(R) \cos(\Phi) \sin(i)$](image)

- Observed radial velocity: $v_r = v_{\text{sys}} + v(R) \cos(\Phi) \sin(i)$
Axisymmetric Disk:

\[ v^2(R) = \frac{GM(r < R)}{R} \]

1) If \( M \sim R \): \( v = \text{const.} \)
   \[ v_r - v_{\text{sys}} \sim \cos(\Phi) \sin(i) \]

2) If \( M \sim R^3 \): \( v \sim R \)
   \[ v_r - v_{\text{sys}} \sim R \cos(\Phi) \sin(i) \]
   (constant density)

3) If \( M = \text{constant} \): \( v \sim R^{-1/2} \)
   \[ v_r - v_{\text{sys}} \sim R^{-1/2} \cos(\Phi) \sin(i) \]
   (point-source mass)
More realistic example

Binney & Merrifield, 506
Radial Velocities from H I 21-cm Emission

- H I gas is better tracer of kinematics than stars:
  - More uniformly distributed and more extensive

- H I typically detected out to 2R_{25} to 4R_{25} (R_{25} of MW ≈ 10 kpc)
- Mass (H I) ≈ 1 to 10% Mass (stellar disk) (Sa ⊢ Sd)

(Sparke & Gallagher, p. 211)
NGC 7331 - HI Intensity and Spider Diagram

(Sparke & Gallagher, p. 210)

Complications: Isophotes twisted in same direction: warped disk
Gradient along minor axis – radial motion
Kinks in isophotes – random motions

linear increase in \( v_r \)
followed by constant \( v_r \)
Rotation Curve (along major axis) for NGC 7331

- Dotted line: CO observations (traces colder molecular gas)
- Points and solid line: H I 21-cm measurements
- Bulge, disk, and gas: deduced from surface-brightness profiles
- Inferred dark halo mass: 2 to 4 times visible mass (in general)

(Sparke & Gallagher, p. 197)
Rotation Curves for Other Galaxies

- Larger disk galaxies rotate faster
- Early types tend to rise more steeply
- Flat rotation curves: evidence for dark halos in disk galaxies

(Sparke & Gallagher, p. 218)
Tully-Fisher Relation

- Rotation curves not possible for more distant spirals
- Use “integrated” H I profile: double-horned common

\[ V_{\text{max}} = \frac{1}{2} W / \sin(i) \]

(Sparke & Gallagher, p. 220)
Ex) Ursa Major Group

Tully – Fisher: \( L_{\text{IR}} \propto v_{\text{max}}^4 \)

Recent calibration: \( \frac{L_I}{4 \times 10^{10} \ L_{I,\odot}} = \left( \frac{v_{\text{max}}}{200 \ \text{km s}^{-1}} \right)^4 \)

(Sparke & Gallagher, p. 221)
Hand-waving Justification for Tully-Fisher:

\[ M(R_d) \propto R_d V_{\text{max}}^2 \]

If M/L ratio is constant:

\[ L \propto R_d V_{\text{max}}^2 \]

Also:

\[ L \propto I_0 R_d^2 \propto I_0 \frac{L^2}{V_{\text{max}}^4} \]

If \( I_0 \) is constant:

\[ L \propto V_{\text{max}}^4 \]

This probably shouldn’t work:

- \( I_0 \) and M/L are not constant with type or luminosity
- Velocities are affected by dark halo, luminosity is not
Spirals

- Even for constant $v(R)$, the angular velocity $(v/R)$ drops with increasing distance
  - differential rotation should wind spirals up
- Theories:
  1) Starburst is stretched out by differential rotation:
     → works for fragmentary (flocculent) arms
  2) Density wave
     → continuous (including grand design) arms
     → pattern speed tends to be much slower than rotation
     → pattern is maintained by self gravity
Two-armed spiral: nested ovals with rotating position angles
Originates from external (another galaxy) or internal (bar) perturbations

(Sparke & Gallagher, p. 219)
Bars

• Not a density wave - “stars remain in bars”
• As with spirals, pattern speed is slower than rotation (up to the co-rotation radius, where bar ends)
• Gas builds up and is shocked on leading edge \(\rightarrow\) infall

(Sparke & Gallagher, p. 235)
Supermassive Black Holes (SMBHs)

- SMBHs have been detected in the gravitational centers of most nearby galaxies.
- Direct methods to detect and measure masses of quiescent SMBHs are based on resolved spectroscopy:

1) Stellar kinematics:
   - Should show rapid rise in $v_r$ and/or $\sigma$ near center.
   - Need high angular resolution (HST or Ground-based AO)
   - Use dynamical models (dominated by ellipticals and bulges).
   - What range of stellar orbits and mass density distributions $\rho(r)$ give the observed $v_r$, $\sigma$, and $\mu$ (2D) distributions?
   - Add a point-source mass (if necessary) to match the core.

2) Measurement of positions, proper motions and radial velocities of individual stars
   - only the Milky Way $\Rightarrow M_\bullet = 4.3 \times 10^6 M_\odot$
1) Stellar Kinematics from HST

Ex) M32 (compact dE)

- HST detected high $v_r$ and $\sigma$ in core.
- Trends smeared out in ground-based telescopes
- SMBH Mass: $M_\bullet \approx 3 \times 10^6 M_\odot$

Why do we need high angular resolution?

- What is the radius of influence for the SMBH in M32?

\[ r = \frac{GM_\bullet}{\sigma_*^2}, \text{ where } \sigma_* = \text{typical stellar velocity dispersion} \]

For M32, \( r \approx 1 \text{ pc} \rightarrow 0.3'' \) at a distance of 725 kpc.

- SMBH “machine”: HST’s Space Telescope Imaging Spectrograph (STIS) – long slit, high resolution spectra
  - angular resolution \( \sim 0.1'' \), velocity resolution \( \sim 30 \text{ km/s} \)
  - measured SMBH masses in many nearby galaxies

- Note these observations do not prove existence of SMBHs

  Ex) M32 mass concentrated within \( \sim 0.3 \text{ pc} \):

  \[ \rho \approx 10^{-15} \text{ g cm}^{-3} ! \] (pretty good vacuum)

  \[ \rightarrow \text{must rely on arguments that stars inside this volume would collide and eventually form a SMBH} \]
What would prove the existence of a SMBH?

• Gravitationally redshifted emission from gas within a few times the Schwarzschild radius ($R_s$)

\[ v_{\text{esc}}^2 = c^2 = \frac{2GM\cdot}{R_s} \rightarrow R_s = \frac{2GM\cdot}{c^2} \]

For M32: $R_s = 9 \times 10^{11}$ cm $\approx 13R_\odot$

$\rightarrow$ projected angular size: $\theta \approx 10^{-7}$ arcsec

• No hope of resolving directly (can’t get rotation curve)

• X-ray observations of AGN have detected gravitationally-redshifted Fe Kα emission (presumably from accretion disk)
2) Individual Stars - Milky Way

- K band observations with NTT, VLT (mostly O and B supergiants)
- Proper motions plus radial velocities give $M_\bullet = 4.3 \times 10^6 M_\odot$
SMBH Mass/Bulge Correlations

• Kormendy et al. found a correlation between SMBH mass ($M_{\bullet}$) and absolute blue magnitude of the bulge/elliptical

- recent studies confirm: $L_{\text{bulge}} \sim M_{\bullet}$
- given a constant M/L ratio: $M_{\bullet} \approx 0.002 M_\text{bulge}$


green – gas kinematics
blue – stellar kinematics
red – $\text{H}_2\text{O}$ maser
Tighter correlations have been found with $\sigma$ (bulge):

1) $M_\bullet \sim \sigma^{3.75}$


- from stellar, gas kinematics, and masers
- $\sigma_e$: velocity dispersion of bulge within half-light radius
2) $M_\bullet \sim \sigma^{4.80}$


$\sigma_c$ – velocity dispersion within 1/8 the effective radius of bulge
3) More Recent Calibration: $M_\bullet \sim \sigma^4$


- based on stellar (circles), gas kinematics (triangles), masers (asterisks)
- previous disagreements probably due to different ways to measure $\sigma$(bulge)

$$\log\left(\frac{M_\bullet}{M_\odot}\right) = (4.02 \pm 0.32)\log\left(\frac{\sigma}{200 \text{ km s}^{-1}}\right) + (8.19 \pm 0.06)$$
Implications

• SMBHs present in all galaxies with a spheroidal component
• For distant galaxies, $M_\bullet$ can be inferred from $\sigma_0$ or $L_{\text{bulge}}$
• SMBHs in AGN have the same mass as quiescent SMBHs for a given spheroidal (bulge) mass ($M_\bullet \approx 0.002 M_{\text{bulge}}$)
  – but AGN are being fueled by infalling gas/stars
  – AGN were much more common in the past. Many quiescent SMBHs are dead remnants of AGN/QSOs.
• How do SMBHs know about their bulges? – linked by evolution?
  1) SMBHs the result of spheroidal core collapse? (which can have densities of $\sim 10^5 M_\odot \text{pc}^{-3}$)
  2) Are SMBHs the seeds of galaxy formation?
  3) Or did SMBHs and spheroids form and grow together?