Photometric Properties of Elliptical Galaxies

- Surface photometry (e.g. GALFIT)
  - Requires accurate flat fields and sky subtraction
  - Mask stars and contaminants
  - Fit ellipses at (say) logarithmic surface brightness levels
  - Adopt average ellipticity and position angle
  - Compute projected radius for each image pixel and bin to create surface brightness profile

- Rapid decrease in surface brightness with radius
- De-projection via Abel integral equation
  - Few analytic pairs \([I(R) \text{ vs. } j(R)]\) exist

Hubble Law:

\[
I(R) = \frac{I_0}{\left(1 + \frac{R}{R_0}\right)^2}
\]

de Vaucouleurs \((R^{1/4})\) law:

\[
I(R) = I_0 \exp \left( -7.67 \left[ \left( \frac{R}{R_e} \right)^{1/4} - 1 \right] \right)
\]

or in surface brightness \((\text{mags/arcsec}^2)\):

\[
\mu(R) = \mu(R_e) + 8.325 \left[ \left( \frac{R}{R_e} \right)^{1/4} - 1 \right]
\]

Sersic law (more general):

\[
I(R) = I_e \exp \left( -b \left( \frac{R}{R_e} \right)^{1/n} - 1 \right)
\]

where \(b = 1.999 n - 0.327 (N > 1)\)
Photometric Properties of Ellipticals: Cores

- **Core Properties of Elliptical Galaxies**
  - Fit cores and envelopes with separate power-law profiles
  - “Nuker” profiles (double power-law):
    \[ I(R) = I_b 2^{(\beta - \gamma)/\alpha} (R/R_b)^{-\gamma} [1 + (R/R_b)^\alpha]^{(\gamma - \beta)/\alpha} \]
  - Power laws (diverge at R = 0):
    \[ j(r) \sim r^{-1.9} \]
  - Cuspy cores (breaks flatter at small R):
    \[ j(r) \sim r^{-0.8} \]
  - Power laws found in lower luminosity ellipticals
    \[ M_v > -20.5 \]
  - Cores found in higher luminosity ellipticals
    \[ M_v < -20.5 \]
  - Low luminosity dwarf spheroidals don’t fit in
    - Dead irregulars?

- **Kormendy’s summary**
  - Average surface brightness of Es falls with increasing luminosity
  - Dwarf spheroidal population distinct from classical elliptical galaxies
  - Globular clusters are not just small ellipticals.
    - Much denser (more tightly bound)
    - No dark matter?
Photometric Properties Galaxies: Spirals

- **Photometric Properties of Spiral Galaxies**
  - Surface photometry
    - Fit ellipses at (say) logarithmic surface brightness levels
    - Adopt average ellipticity and position angle
    - Compute projected radius for each pixel and bin
  - Two components in SB profile
    - Bulge (elliptical-like)
    - Exponential Disk
    - Bulge-Disk decomposition
    - Color gradients
  - Model fits:

For the bulge:

\[ \mu(R) = \mu(R_e) + 8.325 \left( \frac{R}{R_e} \right)^{1/4} - 1 \]

Typical values for \( R_e \) are 0.5-4 kpc.

Integration of intensity yields:

\[ I_{\text{Total}} = 7.22 \pi R_e^2 I_e \]

For the disk:

\[ I(R) = I_0 \exp \left( -\frac{R}{R_d} \right) \]

\[ \mu(R) = \mu_0 + 1.086 \left( \frac{R}{R_d} \right) \]

where \( R_d \) is the disk scale length.

Typical values for \( R_d \) are 2 - 5 kpc.
Kinematic Properties Galaxies: Spirals

- Kinematic Properties of Spiral Galaxies
  - Rotation curves
    - One-dimensional slit spectra
    - Flat rotation curves
      (Rubin)
  - Two-dimensional velocity fields
    - 21-cm velocity fields
    - Integrated spectra
      (Fisher & Tully)
    - Channel maps and Spider diagrams
      (Bosma)
    - ALMA will enable this in CO at high z
Kinematic Properties Galaxies: Ellipticals

• Velocity dispersions in ellipticals
  – Slit and fiber spectra
    • See Brault & White 1971 for General Application of FFTs to Spectroscopy
    • Template Fitting of Elliptical Spectra with Giant Star Spectra as Template
    • Absorption line spectra of Ellipticals
    • K-giant template spectra
    • Fourier quotient method
    • Fitting in Fourier Space
      (Sargent et al 1977)
    • Cross-correlation Method
    • Fitting in Real Space
      (Tonry and Davis 1981)
    • See IRAF XCORR documentation
    • Result is the Line-of-sight Velocity Distribution (LOSVD) function
  – Models
    • Most LOSVDs are well-fit with Gaussian so usually only dispersions are reported
    • Mapping from 2D IFUs is possible
    • Kinematically distinct cores
    • Substructure, etc.
    • Tensor Virial Theorem:
    • \( \frac{V_m}{\sigma} \) vs ellipticity implies flattening of elliptical is due to anisotropy (not rotationally supported)
Scaling Relations of Spiral Galaxies

- **Tully-Fisher Relation**
  - Empirical correlation between the amplitude of disk rotation curves and the luminosity of the galaxy.
  - Remarkable because it implies integrated star formation history is somehow regulated by the DM halo.
    - Star Formation Feedback?
  - Used to measure redshift-independent distances and to measure $H_0$
  - Should provide a measure of galaxy evolution since dark matter and luminous matter should evolve independently.

(Pierce & Tully 1992)
Scaling Relations of Elliptical Galaxies

- **Fundamental Plane**
  - Ellipticals occupy a 3-d plane (Djorgovski & Davis 1987)
  - Predicted by the virial theorem
  - Projection of the plane can result in an indicator of distance
  - Similar to the Tully-Fisher relation but for ellipticals
  - Both relations are calibrated nearby using stars (more about this later) and then used to measure the Hubble Constant over large scales
  - Both relations can be applied at moderate/high redshift in order to parameterize the evolution of galaxies
Nuclei of Galaxies

- Active galactic Nuclei
  - Existence of AGN invites investigation of galactic nuclei
  - Highly collimated jets and rapid variability implies small size of source.
  - More about this later but let’s examine properties of nuclei

- Nearness of M31 allows high spatial resolution
  - Early work identified stellar object as nucleus
  - High spatial resolution imaging showed this to be an error
  - Nucleus is actually the low SB center of the outer isophotes
  - Stellar object is a nearly superimposed globular cluster
  - High resolution spectroscopy showed rapid rotation and a high velocity dispersion.
  - Evidence of a Super Massive Black Hole (SMBH)

- HST provides relatively high resolution capabilities out to the Virgo Cluster (14 Mpc)
  - All galaxies (elliptical and spirals) studied in sufficient detail to date show evidence for an SMBH
Nuclei of Galaxies

- Existence of SMBH suggests their formation requires residence in galactic nucleus (Ferrarese & Merritt 2000; Gebhardt et al. 2000)
  - BH must form from evolution of high mass stars
  - SMBH requires an efficient process for growth
  - Mergers and massive accretion?
  - BHs must form early (high z) and then merge/grow to become SMBHs
  - Low SB disk galaxies seem to have wimpy SMBHs (few mergers?)
- Mass of the SMBH correlates with the mass of the bulge
  - Growth tied together?
  - Mergers could drive both bulge growth and fuel the SMBH
Nuclei of Galaxies

- **Cores of Spiral Galaxies Can Be Complex**
- **Some spiral galaxies have distinct cores**
  - Core has completely different rotational properties than remainder of galaxy
  - Implication is that a merger has driven gas and stars into the nucleus independent of the rest of the disk
  - Dynamical times of nucleus and disk are completely different
  - Nuclear material must be the more recent event
  - Effect seen in both gas (emission lines) and in stars (absorption lines)
- **AGN jet axis often not aligned with spiral galaxy’s rotation axis**
  - Further evidence that nuclear formation and accretion are distinct from the remaining galaxy
Some References

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