Basic Properties of Elliptical Galaxies (Review)

- Have a look at Figure 6.6 in the book
  - Round things occupy a variety of loci on a plot of central surface brightness vs total luminosity

- Surface photometry
  - $I(r) = I_e \exp\{-7.67[(r/r_e)^{1/4} - 1]\}$
  - “$r^{1/4}$” law
  - $R_e$ = effective radius at which $\frac{1}{2}$ of light is emitted
  - Comparable to bulges of disk galaxies

- Classification: E0–E7 describing increase in flattening

- Stellar populations: old, metal rich

- Environment: dense, usually in clusters (morphology–density relationship)
Sample Spectra
Results
We see the 2–dimensional projection of a three dimensional thing: how can we tell the true shape?
- Orbits
- Viewing angle
- Velocity fields

Look for deviations in the 2–dimensional data → twists in the isophotes
- Peng, Ford, Freeman (2004) use planetary nebula to map kinematics in NGC 5128
- PNs → bright, emission line sources, widely distributed
- 1141 PNe → velocity field for N5128
- Twist in isovelocity contours suggests triaxiality

Can do this with stellar velocity fields within the galaxy as well (see papers by Statler et al)
Scaling relationship between size, velocity dispersion, and surface brightness
- Faber–Jackson: $L \sim \sigma^4$

E’s occupy a plane in $r_e$, $\sigma$, $\mu_e$ space
- $r_e \sim \sigma^A \mu^B$ (A~1.3, B~−0.8)

Virial theorem: $<r_e> = <\sigma^2><\mu_e>^{-1}<M/L>^{-1}$

Observed fit: $\log r_e = 0.36(<l>_e/\mu_B) + 1.4\log \sigma$

Why the discrepancy? M/L is not constant? Es are really anisotropic?
Fundamental Plane

The Fundamental Plane for E and S0 galaxies

![Diagram](image)

The Fundamental Plane for E and S0 galaxies is a statistical relationship observed in galaxies, particularly ellipticals and SOs. This relationship is often described by the equation:

\[ \log(r_e) = A - B \log(S) \]

where \( r_e \) is the effective radius, \( S \) is the surface brightness, and \( A \) and \( B \) are constants specific to the sample of galaxies being studied.

This relationship is often used to infer properties of galaxies, such as their mass-to-light ratio. The diagram shows a scatter plot of galaxies on the Fundamental Plane, with the logarithm of the effective radius plotted against the logarithm of the surface brightness.

3.1 Comparison with other authors

The coefficients we derive for the FP agree reasonably well with those obtained earlier in the literature (e.g., Djorgovski & Davis 1987; Faber et al. 1987; Bender et al. 1992; Conroy et al. 1992; Jorgensen et al. 1995; Saglia, Bender & Dionigi 1996). Most of the differences between the various results are due to the fitting method, and the selection of galaxies.

The most common approach to determine the coefficients is a least-squares fit to the residuals minimized in the direction of \( \log(r_e) \). Such a least-squares fit can lead to biased results, as the velocity dispersion and mean surface brightness have significant measurement errors. Furthermore, most samples are selected by apparent magnitude, and the requirement that the observed velocity dispersion is higher than 100 km s\(^{-1}\). This adds further biases to the coefficients.

The bias caused by measurement errors is straightforward to estimate. For uncorrected measurement errors the estimated bias for the coefficient \( A \) of parameter \( g \) is

\[ \log(S) = (a + b \log(r_e) + c \log(S) + d \log(r_e) \log(S)) \]

where \( a, b, c, \) and \( d \) are coefficients.

The least-squares fit in \( \log(r_e) \), for example, produce a systematic bias of the order of 1 per cent for the coefficient \( a \) at a given \( g \) or \( h \). This effect can be partially overcome by minimizing the three parameters separately, and then using some average of the results as the final fit. Further, the three determinations of the coefficients give an idea of the systematic uncertainty in the coefficients. For our sample, we obtain coefficients in the range 1.09 ± 0.17, and 0.75 ± 0.15. This includes the values given above, and all published results lie in this range.

The coefficients also depend on the selection criteria. For example, if the galaxies with \( g > 2.2 \) are excluded, the coefficients shift in a systematic way. For our sample we find

\[ \log(r_e) = 1.35 \log(S) - 0.82 \log(S) \]

where \( x \) is the change in \( r_e \) (in per cent) for galaxies with \( g > 2.2 \). This results in a model that is relatively insensitive to sample selection.

The change in \( r_e \) may vary with the sample used or the method of analysis. Our sample of galaxies in each cluster is not complete to a given limit, and the sampling technique varies from cluster to cluster. If we exclude galaxies with total absolute magnitude...
Fundamental Plane (3-D)
Scaling relationship between size, velocity dispersion, and surface brightness

- Faber–Jackson: \( L \sim \sigma^4 \)

E’s occupy a plane in \( r_e, \sigma, \mu_e \) space

- \( r_e \sim \sigma^A \mu^B \) (\( A \approx 1.3, B \approx -0.8 \))

Virial theorem: \( \langle r_e \rangle = \langle \sigma^2 \rangle \langle \mu_e \rangle^{-1} \langle M/L \rangle^{-1} \)

Observed fit: \( \log r_e = 0.36(\langle I \rangle_e / \mu_B) + 1.4 \log \sigma \)

Why the discrepancy? M/L is not constant? Es are really anisotropic?
Hot Gas and Dark Matter

- $T \rightarrow$ velocity dispersion $\rightarrow$ mass distribution
- Let’s assume hydrostatic equilibrium
  - $\frac{d}{dr}(\rho_{\text{gas}}kT/\mu m_p) = (GM(<r)/r^2)\rho_{\text{gas}}$
  - Direct measure of elliptical mass from X-ray data; also works in galaxy clusters
- Gas temp $> \text{stellar kinetic temp}$
  - $\mu m_p \langle \sigma \rangle^2/k \langle T \rangle \approx 0.5 \rightarrow$ this alone suggest some dark matter; $T_{\text{gas}}/T_*$ ratio increases for low velocity dispersion
X-ray Emission
Hot Gas and Dark Matter

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Stellar Kinematics and DM

- Apply something like the CBE
- Jeans equation for spherical, isotropic stellar system
  - $d(\rho \sigma^2)/dr = -GM(r)\rho/r^2 + \rho V^2/r$
  - Adopt a mass model
    - e.g. isothermal sphere, NFW halo
      - This is only for the dark matter
    - e.g. Hernquist: $\rho(r) = (M_\text{l}/2\pi)(1/r(r+a)^2)$
      - This is only for the luminous matter
  - For N5128, this yields $M/L \sim 12-15$
Again, it’s the photometry game → try to fit some function to the observed light distribution → looking for deviations from “$R^{1/4}$” law

- $I(r)=I_b 2^{(\beta-\gamma)/\alpha}(r_b/r)^{\gamma}[1+(r/r_b)^{\alpha}]^{(\gamma-\beta)/\alpha}$
  - $r_b$ = “break” radius
  - $\gamma$ = inner logarithmic slope ($r < r_b$) → $\gamma = -\text{dlog}I/\text{dlog}r$
  - $\beta$ = outer slope
  - $\alpha$ = sharpness of break

- “core” galaxies ($\gamma > 0$)
- “power law” galaxies – steep surface brightness profile with luminosity densities in center brighter than “core” galaxies – tend to be less luminous, smaller galaxies

Two families of early-type galaxies
- Mergers/BH increase vel dispersion and flatten light profile
- Gas dissipation increases nuclear luminosity
Central Black Holes

- Not just a problem for ellipticals, but that’s where we’ll start...
- How do you tell?
Central Black Holes

- Ellipticals
  - Central surface brightness
  - Velocity dispersions
    - MBH/σ relationship

- Spirals
  - Rotational velocities
  - VLBA measurement of masers in NGC 4258
Case Study: N821
Central Black Holes

- Ellipticals
  - Central surface brightness
  - Velocity dispersions
    - MBH/σ relationship

- Spirals
  - Rotational velocities
  - VLBA measurement of masers in NGC 4258
Formation of Elliptical Galaxies

- **Mergers**
  - Tails and bridges result of tidal forces
  - Two galaxies approach on parabolic orbits
    - Systems pass, turn around, but leave tails behind them
    - Ultimately the systems merge

- **Simulated merger remnants follow** $r^{1/4}$ **law**

- **Observationally…**
  - E+A galaxies look like merger remnants
  - Ellipticals reside in high density environments
Interactions Gallery

Arp 244 = "The Antennae"

HI Rogues Gallery  J. Hibbard
What is this thing?
Galactic Cannibalism

- “dynamical friction” induced cannibalism turns a normal elliptical into a cD giant → several Es have multiple nuclei
- Dynamical friction = braking of some massive body via large numbers of weak gravitational interactions with a distribution of smaller masses (i.e. stars) → satellite, M, deflects stars into building a trailing concentration of stars, increasing the gravitational drag, slowing down the satellite
Cannibalism

- Consider:
  - Satellite with mass, M
  - Stars with mass, m
  - Relative velocity, \( v_0 \)
  - Impact parameter, \( b \)
  - Angle of deflection, \( \theta \)
- “reduced particle”; \( \mu = \frac{mM}{m+M} \)
- Change in velocity parallel to the initial motion
  - \( \Delta v = \frac{2mv_0}{M+m}\left[1 + \left(\frac{b^2v_0^4}{G^2(M+m)^2}\right)^{-1}2\pi bdb\right] \)
  - Then you integrate over impact parameter and some velocity distribution
Applications

- Growth of elliptical galaxies
- Milky Way is swallowing a number of its satellites – could the halo be comprised entirely of tidally stripped stars?
Growth of the Milky Way?

Majewski - real data

Johnston - simulation