Whittle : EXTRAGALACTIC ASTRONOMY

7. ELLIPTICAL GALAXIES

(1) Introduction

(a) The Myths

Our view of Elliptical galaxies has changed greatly :
In the 1970s, Ellipticals were thought to be :

- Diskless bulges with deVaucouleurs ($R^{1/4}$) profiles and constant density (King) cores.
- Oblate spheroids flattened by rotation
- Void of gas and dust
- Contain a single ancient population of stars
- Relaxed dynamically quiescent systems

To a large extent, **all** of the above are now thought to be wrong.

(b) Subdividing the Elliptical Class

In what follows, it will be useful to consider **three** classes of Ellipticals :

- **Luminous** : L greater than 1-few L_*, M_B brighter than about -20
- **Midsize** (including massive bulges) : L between 0.1 L_* & L_*, M_B in the range -18 to -20
- **Dwarfs** : L less than 0.1 L_*, or M_B fainter than -18.

Luminous and midsize have somewhat different properties, but form a single sequence in mass.
dwarf Es are significantly different.

(c) Parameters

Here are a few recurring parameters we need to be familiar with :

- **Surface Brightness (SB)** : several symbols : $I_B(R)$ (flux units), or $\Sigma_B(R)$ (mag/ss units; B = B band)
- **Total flux** : (a) within projected radius $L(<R)$, or (b) integrated : L_{tot} (equivalent to M_B)
- **Effective Radius** : R_e defined as the half light radius : $L(<R_e) = 0.5\ L_{tot}$ [also $I_e = I(R_e)$ and $\Sigma_e = \Sigma(R_e)$]
- **Stellar Velocity Dispersion** : $\sigma_e = <\sigma(<R_e)>$
  assumes a Gaussian projected stellar velocity distribution
  if possible, aperture includes light out to R_e

Also important, are properties of the **core** :

- **Central Surface Brightness** : $\Sigma(0)$
- **Core Radius** : r_c or R_c, such that $I(R_c) = 0.5\ I(0)$
  note : sometimes r_c (or r_b) refers to a **break** in the near nuclear light profile (eg HST Nuker group)
- **Central Stellar Velocity Dispersion** : $\sigma_o = \sigma(0)$

Remember : $I(R)$ and $\Sigma(R)$ are **independent of distance** ! (for small redshifts)

(d) Deprojection

Note that all the above quantities are **projected** onto the sky.
Ultimately we want true 3D spatial information. ie we want to derive :

- the **luminosity density** $j(r)$ from the surface brightness $I(R)$, where
- R is projected radius
- r is true (3D) radius
- for constant M/L ratio, $j(r)$ and $I(R)$ track the space and projected **mass** densities

In general, (see diagram), with $z^2 = r^2 - R^2$ and $dz = r\ dr / (r^2 - R^2)^{1/2}$, we have

$$I(R) = \int_{-\infty}^{\infty} j(r)\ dz = 2\int_R^{\infty} \frac{j(r)\ r\ dr}{\sqrt{(r^2 - R^2)}} \qquad (7.1)$$

This is an Abel Integral equation, with solution

$$j(r) = \frac{-1}{\pi} \int_r^{\infty} \frac{dI}{dR} \frac{dR}{\sqrt{(R^2 - r^2)}} \qquad (7.2)$$

- for certain $I(R)$ functions, $j(r)$ can be expressed algebraically
- for smooth (fitted) profiles, evaluate the integral directly
- for noisy data, use the Richardson-Lucy iterative inversion

Note : if the image is elliptical, a unique inversion is only possible for an axisymmetric figues viewed from the equatorial plane.

Just to orient ourselves, consider a **single power law** of index α (typically, $0.5 < \alpha < 1.5$)

We have :

- $I(R) \propto R^{-\alpha}$
- $j(r) \propto r^{-\alpha - 1}$
- $I(<R) \propto R^{2 - \alpha}$
- $Mass(<r) \propto r^{2 - \alpha}$
- $V_c \propto r^{(1 - \alpha)/2}$ (the circular velocity)

These diverge in a number of circumstances :

- I(0), the central surface brightness, diverges for $\alpha > 0$
- j(0), the central luminosity density, diverges for $\alpha > -1$
- $V_c(0)$, the central circular velocity, diverges for $\alpha > 1$
- $j(\infty)$, the distant luminosity density, diverges for $\alpha < -1$
- I(< infinity), the **total** light & mass, diverge for $\alpha < 2$

(e) Observational Concerns

There are a number of practical difficulties facing accurate surface photometry

- **Sky Subtraction** is critical. Typically one aims for I(R) about 5% to 0.5% of sky.
  Difficult especially with small CCDs which may not extend far enough
- **Seeing** affects the central regions : convolving them with the PSF (typically Gaussian with PL wings) :
  - I(R) turns over into a **flat core** for $R < 1\,\sigma$
  - ellipticity decreases significantly for $R < 4\,\sigma$
  - a_4 is affected even further out
- **Calibration** is often difficult, with typical accuracy only ~5%

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(2) Radial Light Profiles : Fitting Functions

Although the light profiles of Ellipticals are quite similar, there are also subtle but important differences.
Here are some example light profiles [images]

Over the years, a number of analytic expressions have been used to fit I(R) of Elliptical galaxies.
They each have their strengths and weaknesses :

(a) deVaucouleurs ($R^{1/4}$) and Sersic ($R^{1/n}$) Laws

deVaucouleurs noticed that for many ellipticals $\Sigma \propto R^{1/4}$
The fit is usually good over all but the inner and outermost regions (typically 0.03 - 20 R_e) [images]
The law is usually written :

$$I(R) \;=\; I_e \; exp\left(-7.67\;\left[\;(R/R_e)^{1/4} - 1\;\right]\right) \qquad (7.3)$$

It has the following properties :

- $L_{tot} = 7.22\,\pi\,R_e^2\,I_e$
- $I(0) = 2000\,I_e$

- $< I(<R_e)> = 3.61\ I_e$ (which we abbreviate to $< I_e >$ and equivalently $< \Sigma_e >$)
- Asymptotically, at small R, $I(R) \propto R^{-0.8}$ while at large R, $I(R) \propto R^{-1.7}$
- in terms of surface brightness : $\Sigma(R) = \Sigma_e + 8.325[\ (R/R_e)^{1/4} - 1\ ] = \Sigma(0) + 8.325\ (R/R_e)^{1/4}$
- while originally purely empirical, Binney (1982) has shown that the $R^{1/4}$ law arises naturally from a reasonable distribution function.

Unfortunately, deprojection isn't straightforward (however, see Young (1975) for tables of j(r) and other properties)

The deVaucouleurs law is a special case of a more general, **Sersic**, law :

$$I(R) = I_e \, exp\left(-b\left[\ (R/R_e)^{1/n} - 1\ \right]\right) \tag{7.4}$$

Where

- $b = 1.999\ n - 0.327$ (N>1) ensures $0.5\ L_{tot} = I(<R_e)$
- n=4 gives the deVaucouleurs $R^{1/4}$ law with b = 7.67
- n=1 gives an exponential profile with b=1.67
- it turns out (see below) that different n's fit the different classes of Ellipticals

(b) Hubble-Reynolds Law

First Reynolds (1913) and later Hubble (1930) used the following function [images]

$$I(R) = \frac{I(0)}{(1 + R/r_o)^2} \tag{7.5}$$

- for $R < r_o$, I(R) is well behaved, with finite $(dI/dR)_{R=0}$
- for $R >> r_o$ we have $I(R) \propto R^{-2}$ so L_{tot} **diverges** (though only logarithmically).
- the related **Hubble-Oemler** profile avoids this by including an exponential (tidal) cutoff at large R

(c) Modified Hubble Law, Isothermal and King Profiles

The following function avoids some of the above problems, and in addition has other advantages:

$$I(R) = \frac{I(0)}{1 + (R/r_o)^2} \tag{7.6}$$

- at large $R >> r_o$, similar to the Hubble-Reynolds law : $I(R) \propto R^{-2}$ and L_{tot} diverges
- however, it has a simple analytic expression for j(r) :

$$j(r) = \frac{I(0)}{2\ r_o \left[1 + (r/r_o)^2\right]^{\frac{3}{2}}} \tag{7.7}$$

- at small $r < 3r_o$, this j(r) is similar to **isothermal models** (though it differs at large r).

Isothermal models :

- are physically grounded : self-gravitating system with Boltzman distribution in energy (potential + kinetic)
- are physically motivated : violent relaxation (at formation) can lead to this Bolzmann distribution
- at small $R < r_o$, I(R) turns over in a flat core, which has known dynamical properties :
    - central density $\rho(0) = 9\,\sigma(0)^2/4\,\pi G r_o^2$ (where $\sigma(0)$ is the central velocity disperson)
    - core M/L ratio = $\rho(0)/j(0)$ where $j(0)=0.495\ I(0)/r_o$
- at large R, since $j(r) \propto R^{-2}$ we have a **flat rotation curve**, $V_c \sim$ const
- however, because of this, at large R, we have $I(<R) \propto R$ and mass quickly diverges !

To avoid this divergence King modifed the energy distribution :
a modified Boltzmann distribution with cutoff above some threshold.
These **King Models** :

- are not analytic, but are solutions to an ODE (solved by simple integration).
- they are **two parameter** functions :
    - the "core radius" parameter, r_o, is related to the overall binding energy (NB r_o can be larger than r_c, the half-light isophote radius)
    - the energy cutoff leads to a truncation in j(r) at a **tidal radius**, r_t.
    - the models form a sequence in **concentration** $c = \log_{10}(r_t/r_o)$ [images]
- stellar velocity dispersion is ~const across the core, but drops outside
- good fits to Globular clusters are found for c ~ 0.75 - 1.75
- moderate fits to some ellipticals are found for c > 2.2
- c ~ 1.7 is reasonably close to the modified Hubble law.

(d) Dehnen Laws (including Hernquist and Jaffe Laws)

Motivated in part by an observed range in profile gradients, Dehnen (1993) introduces a 3-parameter law :

$$j(r) = \frac{3-\gamma}{4\,\pi}\ \frac{L_{tot}\ r_o}{r^{\gamma}\ (r + r_o)^{4-\gamma}} \qquad (7.8)$$

with corresponding light profile :

$$I(R) = R^{1-\gamma} \int_0^{\infty} \frac{(\sinh\psi)^{1-\gamma}\ d\psi}{(1 + R\cos\psi)^{4-\gamma}} \qquad (7.9)$$

Note several things :

- it is the **luminosity density** that is first specified, the brightness profile is the more complex form.
- at large R, the total light, L_{tot}, is **finite**
- at small R, for $\gamma > 1$, $I(R) \propto R^{1-\gamma}$ and j(r) rises **faster** than r^{-1} (called **cusps**) while for $\gamma < 1$, I(R) ~ const, so j(r) rises **slower** than r^{-1} (called **cores**)
- analytic expressions for I(R) exist for integer and half-integer values of γ

- the γ = 1 model is also called the **Hernquist** law
- the γ = 3/2 model is closest to the $R^{1/4}$ law of deVaucouleurs
- the γ = 2 model is called the **Jaffe** law.
  The Jaffe model is particularly useful since :
  - r_o contains half the **unprojected** light
  - $R_e = 0.76\ r_o$ contains half the **projected** light
  - it yields particularly simple expressions for important physical quantities :

$$L(<r) = L_{\rm tot}\,\frac{r}{r+r_o} \qquad (7.10a)$$

$$\phi(r) = \frac{G\,L_{\rm tot}}{r_o}\left(\frac{M}{L}\right)\ln\frac{r}{r+r_o} \qquad (7.10b)$$

With light profiles given by ($a=R/r_o$) :

$$I(a) = \begin{cases} (4a)^{-1} + \frac{1}{\pi}(1-a^2)^{-1} - (1-a^2)^{-3/2}(2-a^2)\,\mathrm{arcosh}(1/a) & \text{for } a<1 \\ (4a)^{-1} - \frac{1}{\pi}(a^2-1)^{-1} + (a^2-1)^{-3/2}(a^2-2)\,\mathrm{arcos}(1/a) & \text{for } a\ge 1 \end{cases} \qquad (7.11)$$

an example of a Jaffe model fit to NGC 3379 is shown here

A comparison of a number of different models are shown here and here.

(e) Central Regions : the "Nuker" Profile

The above functions aren't adequate for the nuclear regions, as imaged by HST
Lauer et al (1995) introduced a new function for these regions, called the "Nuker" profile :

$$I(R) = I(R_b)\;2^{(\beta-\gamma)/\alpha}\left(\frac{R}{R_b}\right)^{-\gamma}\left[1+\left(\frac{R}{R_b}\right)^{-\alpha}\right]^{(\gamma-\beta)/\alpha} \qquad (7.12)$$

- this is a **five** parameter fit which describes two power laws
- for $R >> R_b$ we have $I(R) \propto R^{-\beta}$ describing the outer power law
- for $R << R_b$ we have $I(R) \propto R^{-\gamma}$ describing the inner cusp or core
- the "break" between the two regions comes at R_b with $I(R_b)$
- α sets the sharpness of the transition near R_b.

An example of two such fits to HST data is shown here.
Notice the significant difference between the two, discussed below in 3b.

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(3) Radial Light Profiles : Resulting Fits

In general, one should distinguish between the most nuclear regions and the overall profile.

(a) Outside the Center

The various 2-parameter functions fit with similar quality (typically ~0.2 mag over a 6 mag range).
The most commonly used is the $R^{1/4}$ law.
These fitting functions do **not**, in general, reproduce the central regions very well
There is some real variation in the outer light profiles.

(i) Variation with Luminosity

Galaxies of different luminosity have somewhat different slopes [images]
The $R^{1/4}$ law fits best near $M_B \sim -21$; too steep for $M_B \sim -22$ and too shallow for $M_B \sim -19$
Sersic and Dehnen functions are useful with their variable slope parameters.

- Lower luminosity Es have **steeper** slopes : (Sersic n< 4 and Dehnen/Jaffe $\gamma \sim 2$ fit well)
- Higher luminosity Es have **shallower** slopes : (Sersic n > 4 and Dehnen/Hernquist $\gamma \sim 1$ fit well)

(ii) Variation with Environment

There is some evidence that outer light profiles can be affected by neighbors :

- Ellipticals in dense clusters have profiles that are **cutoff** at large radii
  likely caused by stars being **lost** due to tidal evaporation
- Ellipticals with a near neighbor can have a **raised** outer profile
  likely caused by **tidal heating** which puffs up the outer envelope

(iii) cD galaxies

cD galaxies are well fit by the $R^{1/4}$ law out to about $20R_e$
Outside this, their light profiles lie **above** the fit (eg $I(R) \propto R^{-1.6}$), in an extended halo [images]
This halo light may **not** come from the galaxy but from stars in the **cluster**

- the stellar velocity dispersion **increases** with radius, as expected for cluster stars
  (note : velocity dispersion usually **drops** with radius in normal Es)
- the isophotes can change to match the **isopleths** of the cluster galaxy distribution.

(iv) Dwarf Ellipticals

There are **two** classes of Dwarf Ellipticals :

- **compact** dEs : these are quite rare, but are clearly a continuation of their more luminous counterparts
  eg M32 which has a reasonable $R^{1/4}$ profile, perhaps slightly steeper, as expected.
- **diffuse** dEs : these are common and are **quite different** from the more luminous Ellipticals

The diffuse dEs have **exponential** light profiles (Sersic with n ~ 1) [images]
Note that these are, however, **not** disks (which also have exponential profiles).
This figure compares dSph with dS+Irr profiles
As we shall see, these diffuse dEs should **not** be thought of as low luminosity ellipticals.

(b) Central Light Profiles

Before ~1975 the **serious** influence of seeing, especially in photographic work, was not appreciated.
The belief in flat King-like cores was shown to be **incorrect** with CCD images (eg Kormendy 1977)
Significant progress was only possible using HST (principally, by the "Nuker" group).

For significant samples, "Nuker" profiles were fitted, and showed :

- There are **very few** cases where I(R) is flat at the center; all continue to rise down to 0.1 arcsec.
- On the outskirts of the nucleus, all profiles are quite steep, $j(r) \propto r^{-2}$
- Closer in, the profiles divide into **two groups** [images] :
  - **power laws** : profile keeps rising steeply : $j(r) \propto r^{-1.9}$ with I(R) diverging at R=0
  - **cuspy cores** : profile breaks to shallower power-law : $j(r) \propto r^{-0.8}$ with I(R) finite at R=0
- remarkably, these two types depend on the galaxy's total **luminosity** :
  - Nuclear **power laws** are found in **Lower** Luminosity Ellipticals and Spiral bulges (L < ~L*)
  - Nuclear **cores** are found in **Higher** Luminosity Ellipticals

The reasons for this are not yet well understood (see below, 4c).

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(4) Correlations Between Parameters

There are many correlations between the various properties of Ellipticals.
The tightness of some are quite remarkable, and point to an underlying homogeneity of this class of galaxy.

(a) Early 2-Parameter Correlations

(i) Color-Magnitude and Similar Correlations

Several correlations exist between :

- parameters tracking metallicity (and/or age) : (B-V) and Mg_2 strength
- parameters of total galaxy mass : M_B and σ_e

Color-Magnitude Relation

- more luminous ellipticals are slightly redder [images]
- see figure for Coma and figure for intermediate z cluster (and picture of cluster itself)

Mg_2 vs Velocity Dispersion

- remarkably tight relation : galaxies with deeper potentials have stronger Mg_2 [images] .
- see figure for ellipticals and S0s

We conclude : more luminous/massive galaxies are more **metal rich** (stronger Mg_2 and blue/UV blanketing)
The reason : deeper potentials hold ISM longer allowing metals to build up
Note : there are similar correlations **within individual galaxies**
Suggests metallicity in fact correlates with **escape velocity**

(ii) Size & Luminosity vs Surface Brightness (Kormendy) Relation

A couple of correlations suggest larger, more luminous galaxies have lower surface brightness

$< I_e >$ correlates with R_e :

- $R_e \propto < I_e >^{-0.83 +/- 0.08}$ (see figure from Kormendy)

$< I_e >$ correlates with L_{tot} :

- $L_{tot} \propto < I_e >^{-2/3}$
- this follows from the above relation, given $L_e = 1/2\ L_{tot} = pi < I_e > R_e^2$

We conclude : larger and more luminous galaxies are **fluffier** with **lower densities**
An interpretation is not yet too clear, though galaxy formation models must explain it.
One inference : low-luminosity ellipticals formed with more gaseous dissipation than giant ellipticals.

(iii) Luminosity vs Velocity Dispersion (Faber-Jackson) Relation

Faber & Jackson (1976) first found that more luminous ellipticals and bulges have deeper potentials

σ_e correlates with L_{tot} :

- $L \propto \sigma_*^n$ with $3 < n < 5$ (see figure)
- the scatter is ~0.6 mag (greater than measurement errors)
- a very rough argument shows why this might apply :
  $V^2 \propto GM/R$ and $SB \propto L/R^2$ (independent of distance)
  squaring the first and substituting the second, we get $L \times SB \times (M/L)^2 \propto V^4$
  If we assume M/L and SB for ellipticals doesn't vary much, then we have $L \propto V^4$
  This underlies both the Tully-Fisher and Faber-Jackson relations.

(b) The 3-Parameter Fundamental Plane

The above 2-parameter correlations have considerable **real scatter** (figure; viewgraph; B&M 4.43)
Furthermore, the residuals in one plot correlate with those in another.
This suggests we look for a tighter correlation among **three** parameters :

- a tilted **plane** of points in 3-D volume, which
- projects onto 2-D planes as the (looser) correlations seen above

The choice of the 3 parameters is not unique
Three choices have been studied --- they are essentially equivalent.

(i) Log R_e, $<\Sigma_e>$, Log σ_e (Djorgovski & Davis 1987)

Here, R_e is in kpc; $<\Sigma_e>$ is in B mag/ss; σ_e is in km/s
[Note : we could have used Σ_e rather than $<\Sigma_e>$ or even $L_{tot} = 2 L_e = 2 \pi R_e^2 <\Sigma_e>$]

Several statistical methods can identify/characterise correlations in n-dimensions :

- Principal Component Analysis (PCA)
- Multiple Linear Regression
- Partial Correlation Analysis

Using these, we find the equation of the **Fundamental Plane** to be :

- $\text{Log } R_e = 0.36 <\Sigma_e> + 1.4 \text{ Log } \sigma_e + \text{const}$ [normal vector (-0.65, 0.22, 0.86)]

Viewed edge on, the plane has very little scatter ~15% (see figure)

(ii) The $D_n - \sigma$ Relation (Dressler et al 1987 : Seven Samurai)

Before the F-P was found, a very tight 2-parameter correlation was identified (figure) :
D_n vs σ_e, at which
D_n = Diameter (in kpc) where $<\Sigma_e> = 20.75$ B mag/ss
(the actual value of 20.75 is not important)

It turns out that this choice of parameters renders the F-P essentially edge-on
Here's why :

For $R^{1/4}$ law, integration gives $D_n \propto R_e <I_e>^{0.8}$ or, equivalently

- $\text{Log } D_n = \text{Log } R_e + 0.8 \text{ Log} < I_e > = \text{Log } R_e - 0.32 < \Sigma_e >$
  (since $< \Sigma_e > = -2.5 \text{ Log} < I_e >$)

Substituting for R_e in the F-P relation, we get :

- $\text{Log } D_n + 0.32 < \Sigma_e > = 0.36 < \Sigma_e > + 1.4 \text{ Log } \sigma_e$
  $\text{Log } D_n = 1.4 \text{ Log } \sigma_e - 0.02 < \Sigma_e >$

and we see that the dependency on $< \Sigma_e >$ has essentially vanished, leaving

$D_n \propto \sigma_e^{1.4}$: a tight 2-parameter correlation

(iii) Kappa Space : κ_1 κ_2 κ_3 (Bender et al 1993)

A deliberate attempt to render the F-P "edge-on" using more physical parameters :

- $\kappa_1 = 2^{-1/2} \text{ Log}(\sigma_e^2 R_e) \propto \text{Log } M$ (M = Mass)
- $\kappa_2 = 6^{-1/2} \text{ Log}(\sigma_e^2 I_e^2 / R_e) \propto \text{Log } [I_e (M/L)^{1/3}]$
- $\kappa_3 = 3^{-1/2} \text{ Log}(\sigma_e^2 / I_e / R_e) \propto \text{Log } (M/L)$

In this K-space we find tight projections in κ_1 vs κ_3 (see figure 1 and figure 2)
this suggests a narrow range of M/L which correlates weakly with total mass

(iv) The Physical Basis of the Fundamental Plane

The following gives some insight into the origin of the F-P relation :
Consider :

- $< I_e > = ½ L_{tot} / pi R_e^2$ (just a definition)
- $M/R_e = c \sigma_e^2$ (virial equilibrium, KE $\propto$ PE; c = "structure parameter" containing all details)

Taken together, these give :

- $R_e = (c/2pi) (M/L)^{-1} \sigma_e^2 < I_e >^{-1}$ or equivalently,
- $\text{Log } R_e = \text{Log } [(c/2pi) (M/L)^{-1}] + 2 \text{ Log } \sigma_e - \text{Log} < I_e >$ or
- $\text{Log } R_e = \text{Log } [(c/2pi) (M/L)^{-1}] + 2 \text{ Log } \sigma_e + 0.4 < \Sigma_e >$ (since $< \Sigma_e > = -2.5 \text{ Log} < I_e >$)

So, **if** c and M/L are constants, then we expect

- $\text{Log } R_e = 2 \text{ Log } \sigma_e + 0.4 < \Sigma_e > + \text{Log } [(c/2pi) (M/L)^{-1}]$

Which is **close to**, but not qute, the F-P relation :

- $\text{Log } R_e = 1.4 \text{ Log } \sigma_e + 0.36 < \Sigma_e > + \text{const}$

To bring these into agreement, we require :

- $(2pi/c) (M/L) \propto M^{1/5} \propto L^{1/4}$

We conclude :

- The F-P is rooted principally in virial equilibrium
- To first order, the M/L ratios and dynamical structures of ellipticals are **very similar**
  This, in turn, suggests the populations, ages & dark matter properties are highly uniform
- There is a weak trend for M/L to **increase** slightly with Mass (× 3 across 5 magnitudes)
- At any point in this relation, the scatter on M/L is only ~10%
- The actual M/L values, ~10-20 (h=1), are consistent with **no** dark matter (within R_e)
- The narrow scatter on F-P and Mg_2 - σ relations place limits on the **ranges** of ages and metallicities :
  Ages ~ 10 - 13 Gyr; Z ~ 2-4 Z(solar)

- None of these relations seems to depend on **environment** : internal properties are relatively robust
- Current work focusses on whether the F-P is different at higher redshift (implications for evolution)

(v) Use of F-P in Distance Measurement

Much motivation for the above work was to improve methods of distance measurement
In general, if a δV (km/s) correlates with a luminosity or size, we have a distance indicator, eg :

- Tully-Fisher : δV_{rot} vs M_I
- Faber-Jackson : σ_e vs M_B

Both the F-P and the D_n- σ relations yield a **physical** length (kpc) from SB & σ, with low scatter (~10-15%)
This has been used to derive **distances** :

- used in the distance ladder to get H_o
- used with cz to map the peculiar velocity field and large scale flows

(c) Core Parameter Correlations

The previous section considered **global** parameters, defined on scales ~R_e
One can instead consider **core** parameters, defined on much smaller scales.
One needs to divide the results into Pre-HST and Post-HST :

(i) Pre-HST Results (eg Kormendy 1985)

This makes use of the best ground based data (CFHT; seeing ~ 0.7 arcsec)
Here, core parameters are defined near ~R_c, where $I(R_c)$ = ½ I(0)
The principal results are shown here for bulges and ellipticals;
Also here or here for wider plots which include dSph, dS-Irr, and GCs (see also S&G 6.6).
Main results :

- **Core** parameters [R_c, $\Sigma(0)$, σ_o] are closely tied to **global** parameters [M_B]
- more **luminous** galaxies have **larger** core radii, with **lower** central surface brightness
- this extends the similar result for global parameters into the cores
- Extreme examples :
  - M32 has R_c = 0.3pc and $\Sigma(0)$ = 11 V mag/ss !
  - M87 has R_c = 800 pc and $\Sigma(0)$ = 17 V mag/ss
- there are **three** different families present, probably with different formation scenarios :
  - ellipticals and bulges (cDs at one end, M32 at the other)
  - dwarfs : dSph, dS and Irr galaxies are **radiacally different**
    they have **much** lower central SB,
    they show the **opposite** trend : more luminous have higher central SB
    they have **exponential** light profiles
    We conclude that dSph and diffuse dEs are NOT simply low luminosity ellipticals,
    they probably formed from dS or Irr galaxies which lost their gas.
  - Globular clusters are different again
    they have central densities comparable to the ellipticals,
    but they do NOT extend the elliptical relations to low luminosities
- Note that the dwarfs and globular clusters fall well **off** the F-P for ellipticals

(ii) Post-HST Results (eg Faber et al 1997, the "Nuker" group)

From 3b above, Nuker profile fits provide somewhat different "core" parameters :
"break radius", R_b, "break surface brightness" and I_b
add to these central dispersion, σ_o; and core luminosity, L_{core} = pi $R_b^2 I_b$

Recall that ellipticals and bulges fall into two classes :

- **Power Law** profiles with no break (R_b is an upper limit) (lower luminosity galaxies)
- **Core** profiles with a break at R_b to a shallower power law (high luminosity galaxies)

To some extent the "core correlations" depend on which group we are talking about.
Here are the results :

- For core galaxies, **core** properties correlate with **global** propertes (figure 1 and figure 2)
  as before, **less luminous** galaxies have **denser** cores
  scaling relations linking core and global properties are shown here
- core galaxies define a fundamental plane (figure)
  the core F-P is approximately parallel to the global F-P
  however, it is 30% thicker (more scattered)
  this scatter may be caused by nuclear Black Holes.
- Power Law galaxies (R_b < 10pc, say) can have densities ~10^3 higher than core galaxies
- Intermediate luminosities (M_V -22 to -20.5) **both** types exist, with range ~10^2 in R_b
- both inside and ouside this range (see below) :
  - Core galaxies are boxy and rotate slowly
  - Power Law galaxies are disky and rotate faster

These relations shed light on differing histories for the two classes (see also below) :

- dissipational or non-dissipational collapse or mergers lead to differing central densities
- Black holes can alter core properties, especially if aquired by tidal capture

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(5) The Shape of Elliptical Galaxies

To first order, isophotes are concentric, aligned, ellipses : (figure)
ellipticity $\epsilon = 1 - b/a$, eccentricity $e = 1 - (b/a)^2$ [$e = \epsilon(2 - \epsilon)$; $\epsilon = 1 - (1 - e)^{1/2}$]
recall, ellipticals are classified En where $n = 10\,\epsilon$

The **apparent** ellipticity combines the **true** shape and **projection** effects
Hence, unlike other morphological designations, n (in En) is not **intrinsic**

(a) 3-D Shapes

We start assuming that surfaces of constant density are **ellipsoidal**

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = r^2 \qquad (7.13)$$

where a, b, c may be functions of r

Basic questions :

- Are ellipticals predominently :
  - **oblate** ie a = b > c (flying saucer)
  - **prolate** ie a > b = c (cigar)
  - **triaxial** ie a > b > c (smooth box)
- what is the **distribution** of true shapes

The distribution of **observed** axial ratios, N(b/a), is shown here
Note : it has a **rise** from E0 to E2, followed by a decline to E7
Can we reproduce this from a random orientation of oblate or prolate ellipsoids?

- projected shape of ellipsoids is more complex than that of disk (eg B&M 4.3.3)

- However, difficult to generate **rising** distribution from E0 to E2 with just oblate or prolate
- **Can** be fit by distribution of triaxial, closer to oblate than prolate :
  - b/a ~ 0.95 (close to oblate)
  - c/a ~ 0.65 (quite flattened)
  - each have Gaussian dispersion ~0.2

The conclusion of triaxiality is supported by the presence of **isophote twists** in many ellipticals

- PA of major axis **changes** with radius (so can ϵ)
- **cannot** result from projection of oblate or prolate shapes
- intrinsically twisted galaxies are not stable
- can occur if triaxial with axial ratios varying with radius.

(b) Isophote Shapes

- isophotes are not **exact** ellipses : typical deviations ~few %
- in general, one can express the isophote as a Fourier series :

$$R(\phi) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\phi) + \sum_{n=1}^{\infty} b_n \sin(n\phi) \quad (7.14)$$

where :

a_0 is the mean radius
a_1, b_1 define the ellipse center
a_2, b_2 define the eccentricity and position angle
a_3, b_3 are useful diagnostics of dust (asymmetries)
Note : a_3 and all b_n are zero for 4-fold symmetry
a_4 defines the boxiness or diskiness (pointiness is better term)

- parameter a_4/a_0 typically in the range -0.02 to +0.04
  $a_4 < 0$: boxy
  $a_4 > 0$: disky
  examples are shown here
- a_4 is **not** very sensitive to presence of an exponential disk; which needs to be
  - quite substantial (~40%), or
  - viewed close to edge on.
  - for sample of Es with $a_4 > 0$, Rix and White (1990) find data consistent with **all** having ~20% disk light

The a_4 parameters are very important since they correlate with many other variables (see below, § 8)

(c) Ripples and Shells

About 10% - 20% of Ellipticals have sharp edged "ripples", of amplitude 3-5%
Here is an example (NGC 3923).
These shells indicate recent accretion of disk galaxies (discussed more in Topic 12)

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(6) Kinematics of Elliptical Galaxies

(a) Methods of Analysis

If stars produced single isolated emission lines, their (projected) velocity field would be easy to find :
the distribution of projected velocities $N(v) \propto F(\lambda)$ ie the emission line profile
However, Ellipticals have complex **absorption line** spectra :
Similar to a K giant, but **broadened** by Doppler motion of the stars.[images]

Consider :

> $S(\lambda)$ = **Stellar Template** = a single star spectrum
> N(v) = relative (normalised) number of stars of **projected** velocity v (ie v_{los})
> note N(v) is usually called the LOSVD (Line Of Sight Velocity Distribution)
> $G(\lambda)$ = observed (broadened) galaxy spectrum

Loosely speaking, $G(\lambda)$ is the same as $S(\lambda)$ convolved (smoothed) by N(v)
We observe $G(\lambda)$ and $S(\lambda)$ and try to obtain N(v).

Details :

- first rebin $G(\lambda)$ and $S(\lambda)$ into pixels of $\delta u = c \ln(\delta\lambda)$ space, ie km/s/pix rather than A/pix
  our convolution is in fact, therefore : G(u) = S(u) ® N(u) (where ® is convolution)
- sum several template stars to match the overall galaxy stellar population
  template **mismatch** is a principle source of error
- subtract a smooth continuum and normalise :
  we dont want line **strength** (ie metallicity) to matter
- remove low frequencies (eg >50A continuum variations) and high frequencies (noise)
  this is achieved in Fourier space : apply filter to FT and transform back **figure**

Several methods have been devised to extract N(v)

(i) Fourier Quotient (Sargent et al 1977)

Writing Fourier transforms (in k space) in **bold** face :
Starting with the galaxy spectrum :

$$G(u) = S(u) \circledR N(u) \qquad (7.15)$$

From the convolution theorem we have :

$$\mathbf{G}(k) = \mathbf{S}(k) \times \mathbf{N}(k) \qquad (7.16)$$

giving [images]

$$\mathbf{N}(k) = \mathbf{G}(k) / \mathbf{T}(k) \qquad (7.17)$$

We **cannot** simply inverse transform **N**(k) because noise is introduced by the division
instead, we **assume** N(v) is **Gaussian**, so **N**(k) is also Gaussian
Estimate **N**(k) by fitting a Gaussian to the quotient
from this fit, we quicky obtain N(v) **as a Gaussian**
thus, the LOSVD is characterized by just cz, σ, and γ (effective line strength)

(ii) Cross Correlation (Tonry and Davis 1979)

It is not difficult to show that :

$$G(u) \copyright S(u) = N(u) \circledR [S(u) \copyright S(u)] \qquad (7.18)$$

where © is **cross-correlation** and ® is convolution
(note S(u) © S(u) is also called **auto-correlation**)

in english : the cross-correlation of the galaxy and template spectra is just the cross-correlation of the template with itself convolved by the broadening function.

In general, cross-correlating the galaxy and template produces an **offset peak**
cross-correlating the template with itself produces a **narrower peak** at **zero offset**
[images]

- the **offset** of the peak from zero gives the redshift
- the **difference in shape** of the two peaks gives the LOSVD
- in practice, only Gaussians are used to model N(u), yielding σ

(iii) Other Methods (more recent)

A number of related methods have been devised since these originals
Many try to extract more information from the LOSVD (ie deviations from Gaussian)
These characterisations include : [images]

- sums of Gaussians of different velocity, width, and strength
- higher classical moments (ie k>2), eg $\zeta_k = \mu^k / \sigma^k$ where μ is the k^{th} moment
  although these are nicely tied to theoretical distribution functions
  they weight the noisy wings too much, so alternatives are better
- Gauss-Hermite functions : h_k (Gaussians multiplied by a poynomial)

Ultimately, we really only deal with two extra parameters for the LOSVD :

- Skewness (k=3), ie asymmetric slope to higher/lower velocities
- Kurtosis (k=4), ie stubby/peaky

In practice, these parameters are evaluated as part of an optimized χ^2 fit
to the observed spectrum of the template convolved by a parameterised LOSVD

(b) Amount of Rotation

(i) Expectations (pre-1975)

Ellipticals should be **rotaionally flattened**
Stellar Dynamical analysis gives, **assuming** axisymmetry and isotropic velocities :

- $(V_r / \sigma_e) \sim [(1-b/a)/(b/a)]^{1/2} = [\epsilon / (1 - \epsilon]^{1/2}$

to compare with observations, lets define :

- $(V_r / \sigma)^* = (V_r / \sigma_e)_{observed} / (V_r / \sigma_e)_{expected}$

(ii) Results

The rotation amplitudes results are shown in a few ways :

- as V_r / σ_e vs ϵ figure
- as $(V_r / \sigma)^*$ vs M_B figure
- as $(V_r / \sigma)^*$ vs a_4 figure

We conclude :

- for **luminous** ellipticals, $(V_r / \sigma)^* < 1$
  not rotationally flattened
  flattened by **velocity anisotropy**
  further evidence for triaxiality
- lower luminosity ellipticals and bulges have $(V_r / \sigma)^* \sim 1$
  are rotationally flattened
  h_3 is large and has opposite sign to V_r
  this suggests we have a broad non-rotating component **plus** a narrow rotating component
  in truth, there may be a continuous distribution

Interestingly, $(V_r / \sigma)^*$ correlates **even better** with a_4/a

as expected :
- disky galaxies rotate
- boxy galaxies dont rotate

(c) Axis of Rotation

Naively, for an axisymmetric rotating galaxy, one expects :
- major axis slit should show **maximum** rotation
- minor axis slit should show **no** rotation
- ie kinematic axis = photometric minor axis

While for a triaxial rotating galaxy, one expects :

- the projected photometric minor axis need not align with any true axis
- the rotation axis can be anywhere in the plane defined by the longest and shortest axes

What do the data suggest ?

Let ψ = the projected kinematic misalignment
= angle between kinematic and photometric minor axes

For some fiducial radius, R_f, a good estimate of this is :

$$\psi_{est} \sim \arctan \left[V_r(R_f) \text{ minor axis} / V_r(R_f) \text{ major axis} \right]$$

A histogram of ψ_{est} shows [images]

- most are ~ 0
- some are 0 - 90
- significant minor-axis rotation occurs in boxy Ellipticals (figure)

As before : while many Ellipticals are close to axisymmetric, some (the boxy ones) are clearly triaxial [images]

(d) Kinematically Distinct Cores and Dust Lanes

~25 % Ellipticals show a **separate**, **rotating** component in the nuclear regions (~1kpc; 0.1-0.3 R_e)
These are called **Kinematically Distinct Cores** (KDC)
Projection effects and difficult detection suggest maybe 30%-60% Ellipticals have KDCs.

Example is shown **here** and **here**

The KDCs show the following :

- rapid rotation $(V_r / \sigma)^* > 1$
  with a range from "warm" to "cold" : $V_r / \sigma = 1$ to 4.5
- kinematic axis aligned with the photometric axis
- some KDCs even **counter-rotate** relative to the host
  Clearly, they have a different (later?) origin than the main galaxy
- they have higher metallicity than the rest of the galaxy **figure**
- photometrically, they are difficult to identify (eg not necessarily disky isophotes) :
  they dont contain much mass
  kinematically prominent in LOSVD because they have **low** σ (eg large h_3)
- may be related to subtle **gas/dust** lanes/disks seen in **many** (~40%) ellipticals
  often randomly aligned at large radii but aligned with minor axis at small radii
  extreme example (NGC 5128) shown **here**

KDCs (and dust lanes) are likely to be a byproduct of dissipational tidal capture

- gas and/or star system captured
- dissipation (loss of orbital energy) occurs :
  stellar system decays by dynamical friction
  gas settles, loosing energy by line radiation
- angular momentum (AM) inherited from merger (not from host)
  at large radii we have random orientation (of gas/dust)
  at center, torques/precession aligns with minor axis
- gas disk undergoes star formation to generates a stellar disk
- stars age and disk becomes photometrically difficult to identify

Conclusion :

formation of ellipticals via single event is only part of story
ongoing mergers/accretion plays at least **some** role in construction of present-day ellipticals

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(7) Mass to Light Ratios

In principle :

Stellar velocities & radius give **Mass**
Photometry gives **Light**
Together, we get M/L ratios

In practice, not so straightforward :

- ideally, need full velocity distribution function at each location
- now possible to build reasonable models using LOSVD (see Topic 8)
- usually, however, we need to assume nearly isotropic velocity field.

(a) Inner Parts

Simple estimates :
assume approximately isothermal and fit a King profile (see 2c above)
gives for central luminosity density, central mass density and central M/L :

- $j(0) = I(0) / 2r_o$
- $\rho(0) = 9\,\sigma(0)^2 / 4\pi G r_o^2$
- $M/L = 9\,\sigma(0)^2 / 2\pi G I(0) r_o$

Typically, $M/L \sim 10\,h\,M_\odot / L_{B,\odot}$ so dark matter **does not** dominate in the center

(b) Outer Parts & Halo

For proper analysis, need to consider **velocity anisotropy**

- σ_r = radial velocity dispersion
  extreme : radial orbits
- σ_θ = tangential velocity dispersion (assume $\sigma_\phi = \sigma_\theta$)
  extreme : circular orbits

Define **anisotropy parameter** : $\beta = 1 - \langle \sigma_\theta^2 \rangle / \langle \sigma_r^2 \rangle$
We have three cases :

- $\beta = 0$: isotropic
- $\beta < 0$: tangential anisotropy
- $\beta > 0$: radial anisotropy

For Jaffe models with β = const, stellar dynamics gives (see Topic 8) :

- $M(r) = (3-2\beta)/(1-\beta)\ \sigma_\theta^2 r / G$

and so for three extreme cases :

- isotropic ($\beta = 0$) : $M(r) = 3\ \sigma_\theta^2 r / G$
- fully tangential ($\beta = -\infty$) : $M(r) = 2\ \sigma_\theta^2 r / G$
- fully radial ($\beta = 1$) : $M(r) = \infty$

Notice that M(r) is sensitive to β if there is strong radial anisotropy.

Can we measure the anisotropy ? Just now able to
β affects h_4 : the LOSVD kurtosis **figure**

- tangential ($\beta < 0$) gives **stubby** LOSVD with $h_4 < 0$
- radial ($\beta > 0$) gives **peaky** LOSVD with $h_4 > 0$

These type of measurements have only recently been achieved **figure**.

Note that if σ **increases** at large R, we **know** σ_θ is increasing
in this case Dark Matter is clearly **present**.

In practice, the most distant tracers of the potential are GCs and PN.
They **do** suggest DM halos are present **figure**
However, better methods exist (see Topic 17)

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(8) Two Kinds of Ellipticals : Boxy and Disky

Summary of properties which differ for **boxy** ($a_4 < 0$) and **disky** ($a_4 > 0$) ellipticals and bulges :

Property	**Boxy ($a_4 < 0$)**	**Disky ($a_4 > 0$)**
Luminosity	high : $M_B < -22$	low : $M_B > -18$
Rotation Rate	slow/zero : $(V_r / \sigma)^* < 1$	faster : $(V_r / \sigma)^* \sim 1$
Flattening	velocity anisotropy	rotational
Rotation Axis	anywhere	photometric minor axis

Velocity Field	anisotropic	nearly isotropic
Shape	moderately triaxial	almost oblate
Core Profile	cuspy core	steep power law
Core Density	low	high
Radio Luminosity	radio loud and quiet 10^{20} - 10^{25} W/Hz	radio quiet < 10^{21} W/Hz
X-ray Luminosity	high	low

Some of these are shown here :

a_4 vs V/sig; ellipticity; offset from F-P; radio luminosity : **figure** and **figure**
a_4 vs V/sig; minor axis rotation : **figure**
a_4 vs radio luminosity; X-ray luminosity; : viewgraph

Note that to first order : Boxy and Disky galaxies have the **same** :

- color-magnitude relation
- Mg_2 vs σ relation
- Fundamental Plane relation

It is still unclear quite how to interpret this dichotomy :
The two types may be closely related, or may have quite different histories

Semi-empirically, Kormendy and Bender suggest a modification to the Hubble diagram **figure**

- Disky Ellipticals form an extension of the S0s
- Boxy Ellipticals lie at the extreme left end
  they may or may not be related to the other ellipticals and S0s

This all has important implications for Elliptical Formation

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(9) Formation of Ellipticals

(Note Mergers and Galaxy Formation discussed more in Topics 12 & 19)

Still unclear -- but we have made progress

(a) Two scenarios discussed

(i) Monolithic Dissipative Collapse

- Early massive gas cloud undergoes dissipative collapse
- Huge starburst **during** collapse
  Note : sub-mm detection of ~10^{10} $M_\odot$ cold gas at z ~ 2-3 with high SFR.
- clumpiness during collapse $\rightarrow$ violent relaxation $\rightarrow$ ~ isothermal
  incomplete violent relaxation $\rightarrow$ non-isothermal & non-isotripic
- probably rotate "rapidly" $\rightarrow$ "Disky" Ellipticals ???

(ii) Hierarchical Mergers

- early universe much denser : eg z ~ 2 density ~ 27 times higher than present
- mergers/interactions probably common
- sequence of galactic mergers, starting with pre-galactic substructures
- galaxies continuue to grow during z ~ 1-2
  Note : HST finds **old** ellipticals at z ~ 0.5
- galaxies fall into clusters and merging ceases (encounter velocities too high)
- random accretions → low AM & anisotropic → "Boxy" Ellipticals ???

(b) Relevant Issues & Problems

(i) The Need for Dissipation (loss of energy)

- High densities (especially in Low-Lum Es) require **dissipation** during formation
  - eg collapse factors of ~10 needed to convert spiral disks to elliptical cores
  - eg at M_B ~ -16, Dwarf Spiral vs M32 we have r_c ~ 700pc vs 1pc and $\Sigma(0)$ ~ 23 vs 11
- unlikely/impossible by mergers of **stellar systems** alone
  such mergers cannot increase the (phase-space) density
  (although dense stellar subsystems can settle to the center intact)
- Dissptation requires **gaseous** collapse/merger & subsequent star formation

(ii) Observational Support for Importance of Mergers

- ongoing mergers are seen (eg NGC 7252, NGC 6240, Arp 220)
  - they have ~ $R^{1/4}$ profiles (in K light)
  - have **high** central (gas) densities ~10^2 $M_\odot pc^{-3}$
    comparable to Ellipticals of similar total mass
  - lie close to the F-P for Ellipticals (σ from CO; photometry in K)
- Brightest cluster galaxies are clearly accreting (eg multiple nuclei)
- ongoing accretion is common in ellipticals :
  - KDCs
  - gas/dust lanes in non-equilibrium configurations
  - ripples & shells

However, be **careful** : dont confuse minor accretion with major merger formation

(iii) Theoretical Support for Importance of Mergers

- Compact groups have expected lifetimes ~10^{8-9}yr → must merge
- n-body simulations of major mergers of two bulge/disk/halo galaxies → $R^{1/4}$
  however, highest densities inherited from pre-existing bulges
- n-body simulations of mergers **including gas** (in SPH formalism) and **star formation** (SFR $\propto \rho(gas)^{1.5}$) yields :
  rapid gas collapse to center (before merger complete) with nuclear starburst
  final profile : dense core with "break" in power-law

(iv) Problems to Overcome

- Dense Nuclei survive mergers -- so why do giant Es have larger **lower density** cores if built from denser bulges and Es ?
- Mergers of Es &/or bulges should destroy the F-P
- GC frequency (per unit luminosity) is ~25 times higher in Es than Spirals
  (maybe GCs form during merger -- eg as in NGC 1275)
- difficult to generate metallicity vs luminosity correlation by merging lower luminosity systems
  (unless metals made during merging starburst)

(c) Hybrid : Merger Induced Dissipational Collapse

Kormendy & Sanders (1992) combine the two formation scenarios :

Similar to Ultra-Luminous Infra-red Galaxies (ULIRGs; eg Arp 220 etc; fig_1 and fig_2), which

- are **mergers**, showing tidal debris etc
- have **high central densities** ~10^2 $M_\odot pc^{-3}$, similar to the central stellar densities of ellipticals
- have similar gas mass and stellar mass in the central regions
  → dissipation has occurred, sending the gas to the center
- there is a huge ongoing starburst, creating a homogeneous metal rich population

We have, in these systems, a substantial dissipative collapse which is associated with a major merger

They speculate that the ULIRGs are **ellipticals caught in formation**

Interestingly, ULIRGs are also thought to be **proto-quasars** :

- feeding (and possible creation of) nuclear black holes
- star formation luminosity comparable to quasar luminosity
- currently hidden by dust (which re-radiates in the far IR)
- ultimately becomes visible when surrounding gas swept clear

The ULIRGs are locally rare --- maybe they were common at high-z
Elliptical formation may be associated directly with the quasar era ?

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