**Elliptical Galaxies**

**Old view:** ellipticals are boring, simple systems
- Ellipticals contain no gas & dust
- Ellipticals are composed of old stars
- Ellipticals formed in a monolithic collapse, which induced violent relaxation of the stars, stars are in an equilibrium state

**Modern view:**
- Most/all ellipticals have hot x-ray gas, some have dust, even cold gas
- Ellipticals do rotate, but most of the kinetic energy support (and galaxy shapes) come from an anisotropic velocity dispersion
- Some contain decoupled (counter-rotating) cores, or other complex kinematics
- Some have weak stellar disks
- Ellipticals formed by mergers of two spirals, or hierarchical clustering of smaller galaxies

**Properties of Elliptical Galaxies**

Dwarf Galaxies

Galaxy Scaling Relations and Their Uses

**Fine Structure in E-Galaxies:**

A Signature of Recent Merging

Dust lanes in E galaxy NGC 1316

Dust is surprisingly common in E’s

Probably it originates from cannibalized spiral galaxies
Elliptical Galaxies: Surface Photometry

Surface brightness of elliptical galaxies falls off smoothly with radius. Measured (for example) along the major axis of the galaxy, the profile is normally well represented by the R^{1/4} or de Vaucouleurs law:

\[ I(R) = I(0) e^{-kR^{1/4}} \]

where k is a constant. This can be rewritten as:

\[ I(R) = I_e e^{-[7.67(R/R_e)^{0.25}-1]} \]

where \( R_e \) is the effective radius - the radius of the isophote containing half of the total luminosity. \( I_e \) is the surface brightness at the effective radius. Typically, the effective radius of an elliptical galaxy is a few kpc.

Other Common Profiles

**Sersic profile:**

\[ \Sigma(r) = \Sigma_0 \exp \left\{ -b_n \left[ (r/r_e)^{1/n} \right] \right\} \]

where \( \Sigma \) is the surface brightness in linear units (not magnitudes), \( b_n \) is chosen such that half the luminosity comes from \( R < R_e \). This law becomes de Vaucouleurs for \( n = 4 \), and exponential for \( n = 1 \).

**Hubble’s profile:**

\[ \Sigma(r) = \frac{\Sigma_0}{(1 + r/r_e)^2} \]

with \( \Sigma_0 \) the central surface brightness, and \( r_0 \) the “core” radius interior to which the surface brightness profile is approx. constant.

Note that the integral under the Hubble profile diverges!

De Vaucouleurs’ Law

\[ \text{De Vaucouleurs' Law} \]

The figure below shows the example of a cD galaxy:

\[ R^{1/4} \text{ profile fits the data very well over some 2 decades in radius} \]

There is an excess of brightness in the outer parts of the galaxy with respect to the standard de Vaucouleurs profile.

In the case of dwarf ellipticals, the deviations occur in the opposite direction.
**Triaxial Ellipsoids**

- In general, the 3-D shapes of ellipticals can be triaxial (A,B,C are intrinsic axis radii):
  - Oblate: A = B > C (a flying saucer)
  - Prolate: A > B = C (a cigar)
  - Triaxial A > B > C (a football)
- Studies find that ellipticals are mildly triaxial, with typical axis ratios:
  
  \[ \frac{A}{B} : \frac{B}{C} \approx 1 : 0.95 : 0.65 \]  
  (with some dispersion, ~0.2)
- Triaxiality is supported by observations of isophotal twists in some galaxies (would not see these if galaxies were purely oblate or prolate)
- It is due to the anisotropic velocity dispersions, which stretch the galaxies in proportion along their 3 principal axes

**Isophote Twisting**

In a triaxial case, the orientation in the sky of the projected ellipses will not only depend upon the orientation of the body, but also upon the body’s axis ratio. This is best seen in the projection of the following 2-D figure:

Since the ellipticity changes with radius, even if the major axis of all the ellipses have the same orientation, they appear as if they were rotated in the projected image. This is called *isophote twisting.*
Isophote Twists

Here is an example of twisted isophotes in a satellite galaxy of Andromeda (M31):

And another:

Isophotes: Deviations From Ellipses

Isophotes are not perfect ellipses. There may be an excess of light on the major axis (disky), or on the “corners” of the ellipse (boxy):

The \textit{diskiness/boxiness} of an isophote is measured by the difference between the real isophote and the best-fit elliptical one:

\[
\delta(\phi) = <\delta> + \sum a_n \cos n\phi + \sum b_n \sin n\phi
\]

where the terms with \(n < 4\) all vanish (by construction), and \(a_4 > 0\) is a disky E, while \(a_4 < 0\) corresponds to a boxy E.

Disky and Boxy Elliptical Isophotes

- Disky/boxy shapes correlate with various other galaxy parameters:
  - Boxy galaxies more likely to show isophotal twists (and hence be triaxial)
  - Boxy galaxies tend to be more luminous
  - Boxy galaxies have stronger radio and x-ray emission
  - Boxy galaxies are slow rotators, more anisotropic
  - In contrast, disky galaxies are midsized ellipticals, oblate, faster rotators, less luminous in radio and x-ray
- Some believe that more dissipationless mergers lead to more boxy galaxies, whereas any embedded disks imply some dissipative collapse, but the real picture is probably more complicated
The Kinematics of E-Galaxies

Stars in E galaxies have some ordered motions (e.g., rotation), but most of their kinetic energy is in the form of random motions. Thus, we say that ellipticals are pressure-supported systems.

To measure the kinematics within galaxies we use absorption lines. Each star emits a spectrum which is Doppler shifted in wavelength according to its motion. Random distribution of velocities then broadens the spectral lines relative to those of an individual star. Systemic motions (rotation) shift the line centroids.

2-Dimensional Kinematics of E-Gal’s

Intensity
Rotation velocity
Velocity dispersion

Kinematical Profiles of E-Galaxies

- Rotation is present, but generally not a dominant component of the kinetic energy
- Velocity dispersion tends to be higher closer to the center

Velocity Anisotropy in Elliptical Galaxies

The ratio of the maximum rotational velocity $V_m$ and the mean velocity dispersion $\sigma$ indicates whether the observed shapes of E’s are due to rotation or anisotropic pressure.

Galaxies on this line are flattened by rotation
Galaxies below it are flattened by anisotropy

**Figure 3** – The quantity $V_m/\sigma$ against ellipticity. Ellipticals with $M_r < -20.5$ are shown as filled circles; ellipticals with $M_r > -20.5$ as open circles, and the bulges of dark galaxies, as crosses. The solid line shows the $V_m/\sigma$ relation for oblate galaxies with isotropic velocity dispersions (Binney 1978).
Velocity Anisotropy in Elliptical Galaxies

Now normalize by the “isotropic rotator” line

Rotational Properties of Elliptical Galaxies:

\[ \frac{\left( \frac{\sigma}{\langle v \rangle} \right)^2}{\frac{\sigma}{\langle v \rangle}} = \frac{\langle v \rangle}{\sigma_{\text{observed}}} = \frac{\langle v \rangle}{\sigma_{\text{rot, flattened}}} \]

More luminous ellipticals tend to be anisotropic

This can be understood as a consequence of merging

Stellar Populations in Ellipticals

- Ellipticals are made mostly from old stars, ages > 1 Gyr and generally ~ 10 Gyr
- They have a broad range of metallicities (which indicate the degree of chemical evolution), up to 10 times Solar!
- More metal rich stars are found closer to the center
- This is observed as line strength gradients, or as color gradients (more metal-rich stars are redder)

Metallicity-Luminosity Relation also known as the Color-Magnitude Relation

There is a relation between the color (a metallicity indicator) and the total luminosity or velocity dispersion for E galaxies:

Brighter and dynamically hotter galaxies are redder. This could be explained if small E galaxies were younger or more metal-poor than the large ones. More massive galaxies could be more effective in retaining and recycling their supernova ejecta.

Hot Gas in Elliptical Galaxies

The gas is metal-rich, and thus at least partly a product of stellar evolution. It is at a virial temperature corresponding to the velocity dispersion of stars. Another good probe of dark matter in ellipticals…
The Cores and Nuclei of Ellipticals

Profiles of elliptical galaxies can deviate from the R^{1/4} law at both small and large radii. Close to the center:
- Some galaxies have cores - region where the surface brightness flattens and is ~ constant
- Other galaxies have cusps - surface brightness rises steeply as a power-law right to the center

A cuspy galaxy might appear to have a core if the very bright center is blurred out by atmospheric seeing. Thus, HST is essential to studies of galactic nuclei!

It turns out that:
- The most luminous ellipticals have HST-resolved cores
- Low luminosity ellipticals have power law cusps extending inward as far as can be seen

Central Surface Brightness Profiles

To describe these observations, we can use a new profile suggested by the “Nuker” team:

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

It is a broken power law:
- Slope of \(-\gamma\) at small radii
- Slope of \(-\beta\) at large radius
- Transition between the two slopes at a break radius \(R_b\), at which point the surface brightness is \(I_b\)
- Remaining parameter \(\alpha\) controls how sharp the changeover is
Massive Black Holes in Galactic Nuclei

- It turns out that they are ubiquitous: nearly every non-dwarf galaxy seems to have one, but only a small fraction are active today; these super-massive black holes (SMBH) are believed to be the central engines of quasars or other AGN.
- They are detected through central velocity dispersion or rotation cusps near the center - requiring more mass than can be reasonably provided by stars.
- Their masses correlate very well with many of their host galaxy properties, suggesting a co-formation and/or co-evolution of galaxies (or at least their old stellar spheroid components) and the SMBHs they contain.
- Understanding of this connection is still not complete, but dissipative mergers can both drive starbursts and fuel/grow SMBHs.

Many (all?) ellipticals (& bulges) have black holes- even compact ones like M32!

Can measure BH masses for galaxies via their velocity dispersion.

Fundamental Correlations Between SMBH Masses and Their Host Galaxy Properties

\[
\log \frac{M_{\text{BH}}}{M_\odot} = (-0.36 \pm 0.09) \log \sigma + (1.2 \pm 1.9)
\]

\[\chi^2 = 23\]

Kormendy & Richstone 1995

\[
\frac{M_{\text{BH}}}{M_\odot} = (1.7 \pm 0.3) \times 10^4 \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^{4.6 \pm 0.5}
\]

\[\chi^2 = 0.72\]

Ferrarese & Merritt 2000; Gebhardt et al. 2000

Local SMBH Demographics and Comoving Mass Density

- \( M_\bullet \) from the \( M_\bullet - \sigma \) relation
- \( M_{\text{bulge}} \) from Magorrian et al. (1998)

Mass density in local SMBH:
\[
x = \frac{M_\bullet}{M_{\text{bulge}}} \sim 0.13\%
\]

\( \rho_{\text{bulge}} \sim 3.7 \times 10^8 \, M_\odot \, \text{Mpc}^{-3} \)
(Fukugita et al. 1998)

\[\rho \sim 4.9 \times 10^5 \, M_\odot \, \text{Mpc}^{-3}\]

Recall that the normalization of the GLF is \( \phi_\ast \sim 10^{-2} \, \text{Mpc}^{-3} \), so an average galaxy should contain a \( \sim 10^7 \, M_\odot \) black hole!
Dwarf Galaxies

- Dwarf ellipticals (dE) and dwarf spheroidals (dSph) are a completely different family of objects from normal ellipticals - they are not just small E's.
- In fact, there may be more than one family of gas-poor dwarf galaxies ...
- Dwarfs follow completely different correlations from giant galaxies, suggestive of different formative mechanisms.
- They are generally dark matter (DM) dominated, especially at the faint end of the sequence.
- One possible scenario is that supernova (SN) winds can remove baryons from these low-mass systems, while leaving the DM, while the more massive galaxies retain and recycle their SN ejecta.

Parameter Correlations

- The SMBH - Host Galaxy Correlations
  - $M_{\bullet} \sim M_{\ast}^{4.4}$
  - $M_{\bullet} \sim M_{\ast}^{1.6}$

The SMBH - Host Galaxy Correlations

- $M_{\ast} \sim M_{\bullet}$
- $M_{\bullet} = (0.046) \left( \frac{M_{DM}}{10^{12} M_{\odot}} \right)^{1.57}$

Dark halo mass vs. SMBH mass

( Ferrarese 2002)
**Galaxy Scaling Laws**

- When correlated, global properties of galaxies tend to do so as power-laws; thus “scaling laws”
- They provide a quantitative means of examining physical properties of galaxies and their systematics
- They reflect the internal physics of galaxies, and are a product of the formative and evolutionary histories
  - Thus, they could be (and are) different for different galaxy families
  - We can use them as a fossil evidence of galaxy formation
- When expressed as correlations between distance-dependent and distance-independent quantities, they can be used to measure relative distances of galaxies and peculiar velocities: thus, it is really important to understand their intrinsic limitations of accuracy, e.g., environmental dependences

**Mean Surface Brightness vs. Absolute Mag.**

- A well-defined luminosity vs. rotational speed (often measured as a H I 21 cm line width) relation for spirals:
  
  \[ L \sim V_{\text{rot}}^{\gamma}, \gamma \approx 4, \text{ varies with wavelength} \]

  Or: \( M = b \log (W) + c \), where:
  - \( M \) is the absolute magnitude
  - \( W \) is the Doppler broadened line width, typically measured using the HI 21 cm line, corrected for inclination \( W_{\text{true}} = W_{\text{obs}} \sin(i) \)
  - Both the slope \( b \) and the zero-point \( c \) can be measured from a set of nearby spiral galaxies with well-known distances
  - The slope \( b \) can be also measured from any set of galaxies with roughly the same distance - e.g., galaxies in a cluster - even if that distance is not known
- Scatter is \( \sim 10-20\% \) at best, better in the redder bands
**Tully-Fisher Relation in Different Bands**

Low surface brightness galaxies follow the same TF law as the regular spirals: so it is really relating the baryonic mass to the dark halo.

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**Why is the TFR So Remarkable?**

- Because it connects a property of the dark halo - the maximum circular speed - with the product of the net integrated star formation history, i.e., the luminosity of the disk.
- Halo-regulated galaxy formation/evolution?
- The scatter is remarkably low - even though the conditions for this to happen are known not to be satisfied.
- There is some important feedback mechanism involved, which we do not understand yet.
- Thus, the TFR offers some important insights into the physics of disk galaxy formation.

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**Deriving the Tully-Fisher Relation**

In part, Tully-Fisher relation reflects dynamics of a disk galaxy. Estimate the luminosity and maximum circular velocity of an exponential disk of stars:

Empirically, disk galaxies have an exponential surface brightness profile:

\[ I(R) = I(0) \ e^{-R/h_R} \]

Integrate this across annuli to get the total luminosity:

\[ L \propto \int_{0}^{\infty} 2\pi R I(0) e^{-R/h_R} \, dR \]

\[ L \propto I(0) h_R^2 \]

If the mass of the exponential disk dominates the rotation curve, then the enclosed mass within radius \( R \) will be proportional to the enclosed luminosity:

\[ M(R) \propto L(R) \propto \int_{0}^{R} 2\pi R' I(0) e^{-R'/h_R} \, dR' \]
**The Kormendy Relation**

Larger ellipticals are more diffuse

Re ~ 1.8 hR

Effective radius

Mean surface brightness

**Approximately**, use formula for spherical mass distribution to get \( V(R) \):

\[
V^2(R) \propto \left[ \frac{h_R}{R} - \frac{h_R}{R} e^{-R/h_R} - e^{-R/h_R} \right] \times h_R
\]

Dependence on \( R \) always occurs via the combination \( R / h_R \)

Function in [...] peaks at \( R \sim 1.8 h_R \)

Conclude that: \( V_{\text{max}} \propto \sqrt{h_R} \)

Eliminate \( h_R \) using previous result:

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

But we assumed:
1. \( I(0) = \text{const.} \)
2. \( (M/L) = \text{const.} \)

Both are incorrect!

**The Faber-Jackson Relation**

Analog of the Tully-Fisher relation for spirals, but instead of the peak rotation speed \( V_{\text{max}} \), measure the velocity dispersion. This is correlated with the total luminosity:

\[
L_V = 2 \times 10^{10} \left( \frac{\sigma}{200 \text{ km/s}} \right)^4 L_{\text{sun}}
\]

**Can We Learn Something About the Formation of Ellipticals From the Kormendy Relation?**

From the Virial Theorem, \( m \sigma^2 \sim GmM/R \)

Thus, the dynamical mass scales as \( M \sim R \sigma^2 \)

Luminosity \( L \sim I R^2 \), where \( I \) is the mean surface brightness

Assuming \( (M/L) = \text{const.}, M \sim I R^2 \sim R \sigma^2 \) and \( I R \sim \sigma^2 \)

Now, if ellipticals form via dissipationless merging, the kinetic energy per unit mass \( \sim \sigma^2 \sim \text{const.} \), and thus we would predict the scaling to be \( R \sim I^{-1} \)

If, on the other hand, ellipticals form via dissipative collapse, then \( M = \text{const.} \), surface brightness \( I \sim M R^{-2} \), and thus we would predict the scaling to be \( R \sim I^{-0.5} \)

The observed scaling is \( R \sim I^{-0.8} \). Thus, **both** dissipative collapse and dissipationless merging probably play a role
**Fundamental Plane Relations**

- A set of bivariate scaling relations for elliptical galaxies, including relations between distance dependent quantities such as radius or luminosity, and a combination of two distance-independent ones, such as velocity dispersion or surface brightness
- In a set of ~ 10 independently measured global parameters, there are only 2 statistically independent ones
- Scatter ~ 10%, but it could be lower?

**Different Views of the FP**

Commonly expressed as a bivariate scaling relation \( R \sim \sigma^{1.4}I^{-0.8} \)
Where \( R \) is the radius, \( I \) the mean surf. brightness, \( \sigma \) the velocity disp.

**Scaling Relations for Ellipticals**

- Kormendy rel’n
- Faber-Jackson rel’n
- Cooling diagram
- Fundamental Plane

**Different Views of the FP**

Luminosity instead of radius
Mg abs. line strength index (a measure of metallicity) instead of velocity dispersion
FP connects stellar populations and dynamical and structural parameters of ellipticals
**Deriving the Scaling Relations**

Start with the Virial Theorem:  \[ \frac{GM}{\langle R \rangle} = k_E \frac{\langle V^2 \rangle}{2} \]

Now relate the observable values of \( R, V \) (or \( \sigma, L \), etc., to their “true” mean 3-dim. values by simple scalings:

\[ R = k_R \langle R \rangle \quad V^2 = k_V \langle V^2 \rangle \quad L = k_L I R^2 \]

One can then derive the “virial” versions of the FP and the TFR:

\[ R = K_{SR} V^2 I^{-1} (M/L)^{-1} \]
\[ L = K_{SL} V^4 I^{-1} (M/L)^{-2} \]

Where the “structure” coefficients are:

\[ K_{SR} = \frac{k_E}{2Gk_R k_L k_V} \]
\[ K_{SL} = \frac{k^2_L}{4G^2 k_R k_L k_V} \]

Deviations of the observed relations from these scalings must indicate that either some \( k \)'s and/or the \( (M/L) \) are changing.

**Fundamental Plane and M/L Ratios**

Write the FP scaling relation as:  \[ R \sim \sigma^A I^B \]

Where the observed values are \( A \sim 1.4, B \sim -0.8 \), uncertain by about 10%, and depending on the bandpass.

Recall from Virial Theorem:  \[ \langle R \rangle \sim \langle V^2 \rangle \langle I \rangle^{-1} (M/L)^{-1} \]

Then  \[ k_V^{-1} \quad k_I^{-1} \quad k_R (M/L) \sim \sigma^{A-2} I^{-B-1} \]

If all ellipticals have the same structure, i.e., they are just scaled versions of each other (a homologous family), then all \( k_x = \text{const.} \) and all change must be in \( (M/L) \). Approximately,

\[ (M/L) \sim L^{\alpha} \] \text{, where } \alpha \sim 0.2 \text{ (visible)} \text{ or } \sim 0.1 \text{ (IR)}

But we know that E’s are not a homologous family, so the tilt of the FP must have complex reasons.

**Comments on the Scaling Relations**

- Probably the most challenging thing to understand about these galaxy scaling relations is their thinness: we can understand their slopes, but not why they are so sharply defined: intrinsic spread in many coefficients and/or \((M/L)\) should thicken them considerably - but for some reason it does not. This is still a great mystery.
- Other stellar systems, from globular clusters to clusters of galaxies have fundamental scaling relations of their own.
- We use these relations as distance indicators, assuming that they are universal; but small systematic variations in their slopes or intercepts, e.g., in different environments, would introduce systematic distance errors and spurious peculiar velocities.
  - There is some evidence for that…
The Galaxy Parameter Space

A more general picture

Galaxies of different families form 2-dim. sequences in a 3+ dimensional parameter space of physical properties, much like stars form 1-dim. sequences in a 2-dim. parameter space of \( \{L,T\} \) - this is an equivalent of the H-R diagram, but for galaxies.

The Dark Halos

- Many of galaxy scaling relations may be driven by the properties of their dark halos.
- It is possible to infer their properties from detailed dynamical profiles of galaxies and some modeling.
- Numerical simulations suggest a universal form of the dark halo density profile (NFW = Navarro, Frenk & White):

\[
\frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}
\]

(but one can also fit another formula, e.g., with a core radius and a finite central density).

Dark Halo Scaling Laws

- \( \rho_0 \sim L_B^{-0.35} \)
- \( r_c \sim L_B^{0.37} \) (fits to Sc-Im only)
- \( \sigma \sim L_B^{0.20} \)

so expect the surface density \( \Sigma \sim \rho_0 r_c \) to be \( \sim \) constant over this range of \( M_B \), and it is

Kormendy & Freeman 2003