Elliptical galaxies

Elliptical galaxies look very simple...

• roughly round
• smooth light distribution
• no obvious patches of star formation
• no obvious strong dust lanes (except sometimes...)

...but they’re really not! Detailed studies show significant complexity:

• large range of shapes: oblate to triaxial
• large range of luminosities and concentrations
• rotation vs. pressure support
• cuspy vs. cored centers
• complex star formation histories

Elliptical galaxies

Generically, elliptical galaxies are classified by their luminosities:

- **Giant** \( L > L^* \)
- **Intermediate** \( \sim 3 \times 10^9 L_\odot < L < L^* \)
- **Dwarf** \( L < 3 \times 10^9 L_\odot \) or \( M_B > -18 \) mag

Unlike for disc galaxies, where Hubble types can cover a large range in luminosity, these classes have physical relevance

Ellipticals (and most S0 galaxies) are predominantly a one-parameter family: an elliptical galaxy’s properties depend primarily on its mass
Elliptical galaxies have very smooth profiles over 2 orders of magnitude in radius, usually falling off as $R^{1/4}$.

Light in ellipticals is highly concentrated.

Surface brightness profiles

For giant elliptical galaxy: as $f(R)$ and $f(R^{1/4})$.

The surface brightness falls 9 magnitudes from centre to outskirts: $10^{-9}$ fall-off in projected luminosity.

The light in elliptical galaxies is quite centrally concentrated.

Sources of Error

Sky Background Subtraction – if the sky is over or under subtracted this can have a dramatic effect on the shape of the profile.

Sources include: light pollution from nearby cities, photochemical reactions in the Earth’s upper atmosphere, the zodiacal light, unresolved stars in the Milky Way, and unresolved galaxies.

Seeing effects – unresolved points are spread out due to effects of our atmosphere, quantified by the Point Spread Function (PSF) FWHM ($\sigma$) on the images:

- makes central part of profile flatter
- makes isophote rounder

Some properties of the de Vaucouleurs law

Starting from $I(R) = I_e \times 10^{-3.33[(R/R_e)^{1/4} - 1]}$

...and the definition that half of the light is emitted within $R_e$ we can deduce the following:

The total light of a galaxy that follows a de Vaucouleurs profile is $7.22\pi R_e^2 I_e$

The central surface brightness is $I_0 = 10^{3.33} I_e \approx 2000 I_e$

and the mean surface brightness contained within $R_e$ is $\langle I \rangle_e = 3.61 I_e$
Sérsic Profile

Generalised version of $r^{1/4}$ law is frequently used in which $1/4$ is replaced by $1/n$. Often called Sérsic (1968) models have been shown (Caon et al 1993) to be an even better fit to E's, though it increases the number of free parameters:

$$\mu(r) = \mu_e + 8.3268 \left( \left( \frac{r}{r_e} \right)^{1/n} - 1 \right) \text{ mag arcsec}^{-2}$$

Where $\mu_e$, $r_e$, and $n$ are all free parameters used to obtain the best possible fit to the actual surface brightness profile.

Outskirts

Elliptical galaxies in the centers of clusters with extended, “too-bright” profiles are called cD galaxies. cDs are amongst the brightest of all galaxies.

Centres

Observations from space suffer no seeing because there is no atmosphere! Don’t think that space observations have a $\delta$-function PSF though — the optics themselves impose a PSF.

Ellipticals have either a core: giant ellipticals
cusp: intermediate ellipticals (note that there is still a break radius)
Centres of Elliptical Galaxies

- $R^{1/4}$ and Sersic fits tend to fail in the inner regions of Elliptical
- Regions of special interest because they host supermassive black holes
- Need HST since largest E’s lie far away and seeing effects degrade profile centers

- More luminous E’s ($M_v<-21.7$) tend to have cores, where the SB profile flattens towards center
- Midsize E’s (-21.5<$M_v$<-15.5 with L<2x10$^{10}L_\odot$) are typically core-less systems where the SB profile steeply rises to centre

- Cores could be the result of mergers so central nucleus is more diffuse – caused by binary BHs scouring out centers in “dry mergers” (no gas)
- Core-less also reveal “extra light” which may be result of nuclear starburst resulting from “wet mergers” (with gas)

Isophotal analysis of elliptical galaxies

Elliptical galaxies have (obviously) elliptical isophotes with ellipticities $e = 1 - (b/a)$ where $a, b$ are the semi-major and minor axes of the ellipse

In the traditional Hubble sequence, ellipticals are classified by the apparent ellipticity: $E_n$, where

$$n = 10[1 - (b/a)] = 10e$$

Isophotes are rarely perfect ellipses

Excess of light in the “corners” of the ellipse: boxy

Excess of light along the principal axes: disky

Shapes of elliptical galaxies

What can we learn about the intrinsic shapes of elliptical galaxies from the observed distribution of their axis ratios?

In the most general case, the luminosity density $\rho(x)$ can be expressed as $\rho(m^2)$, where

$$m^2 = \frac{x^2}{\alpha^2} + \frac{y^2}{\beta^2} + \frac{z^2}{\gamma^2}$$

The contours of constant density are ellipsoids with $m^2=$constant

$\alpha \neq \beta \neq \gamma$: triaxial

$\alpha = \gamma < \beta$: prolate (cigar-shaped)

$\alpha = \gamma > \beta$: oblate (pancake-shaped)
Family of ellipsoids

- Oblate
- Prolate
- Triaxial

Deviation from elliptical isophotes: $a_4$

The diskiness/boxiness of an isophote is measured by the difference between the real isophote and the best-fit ellipse:

$$\delta(\phi) = \langle \delta \rangle + \sum_{n} (a_n \cos n\phi + b_n \sin n\phi)$$

If the isophotes have 4-fold symmetry (typical), then terms with $n<4$ and all $b_n$ should be small, and $a_4$ gives the shape:

- $a_4 < 0$: boxy
- $a_4 > 0$: disky

Isophote twisting

If the intrinsic shape of a galaxy is triaxial — that is, all three principal axes have different lengths — then the orientations of the projected ellipses depend on the inclination of the galaxy to the line of sight and the galaxy’s true axis ratios.

Because the ellipticity changes with radius, even if the major axis of all the ellipses have the same true orientation, they will appear as if they were rotated in the projected image.

This is isophote twisting.

Isophote twisting is generally taken to imply triaxiality, but it is impossible to distinguish a real twist from true triaxiality from images alone...

NGC 205, one of the dwarf elliptical companions of M31, has strongly twisted isophotes

compare upper shallow image to lower deep image

likely due to tidal effects in this case!
In general,

Boxy galaxies are
• more luminous
• more likely to show isophote twists
• probably triaxial

Disky galaxies are
• intermediate ellipticals
• often oblate
• faster rotators

Are Ellipticals really so smooth?

Shells - seen at faint levels around most E’s
- Origin could be merger remnants or captured satellites
- prominent shells goes with evidence for some young stars in the galaxy

Dust - visible dust clouds seen in many nearby E’s (maybe 50% of E’s have some - but not much – dust)

Kinematics of elliptical galaxies

How do we measure velocities in elliptical galaxies?

Use the absorption lines in the spectrum, which is the composite spectrum of all of the stars in the galaxy

Each star emits a spectrum which is then Doppler-shifted in wavelength according to its motion, which widens the absorption lines.
Rotation of Ellipticals

Low luminosity Ellipticals and bulges rotate rapidly and have nearly isotropic velocity dispersions and are flattened by rotation.

Bright Ellipticals rotate slowly and are pressure supported and owe their shapes to velocity anisotropy.

Because the relaxation times of elliptical galaxies are much longer than a Hubble time, these galaxies "remember" their formation.

Scaling relations of elliptical galaxies

One of the earliest known structural scaling relations was the Faber-Jackson relation: 

$$ L \propto \sigma^4 $$

A natural consequence of the virial theorem.

Plenty of scatter, and the slope of the relation is different than the virial theorem.

This was assumed to indicate a missing parameter... and there was originally a lot of debate about what was the missing parameter.
Multi-parameter correlations: the Fundamental Plane

A break through in our understanding of scaling laws came from large homogeneous data sets (from CCDs & long-slit spectroscopy), and the application of statistical tools.

**plane** - means correlation in a 3D space and we see this space with three parameters that “see” the correlation from different angles.

### Ellipticals: Fundamental Plane

\[ R \propto \sigma^{1.24} \langle I \rangle_e^{-0.82} \]

- **Radius**
- **Velocity Dispersion**
- **mean Surface Brightness**

### The Fundamental Plane

Where does the Fundamental Plane of elliptical galaxies come from?

Assume the Virial Theorem holds, then the mass is

\[ M = \frac{V^2 R}{G} \]

Divide this by the area to get the mass surface density:

\[ \eta = \frac{V^2}{\pi R^2} \propto \frac{V^2}{R} \]

The surface brightness is this divided by the mass-to-light ratio:

\[ I = \eta \left( \frac{M}{L} \right)^{-1} \]

Combining this:

\[ I \propto \frac{V^2}{R(M/L)} \]

Rewrite this in terms of the radius \( R_e = R \) and identifying the velocity \( V \) as the velocity dispersion \( \sigma \), we have

\[ R_e \propto \left( \frac{M}{L} \right)^{-1} \sigma^2 \langle I \rangle_e^{-1} \]

But note the observed coefficients aren’t 2 & -1 (they are 1.25 and -0.8) and so

\[ \frac{M}{L} \propto L^{1/4} \]

observed relation:

\[ R \propto \sigma^{1.24} \langle I \rangle_e^{-0.82} \]
The Fundamental Plane

That is, the mass-to-light ratios of ellipticals increase as they become more luminous (or more massive).

...if (and only if) the structure of ellipticals doesn’t change as a function of luminosity (or mass).

Why is this?
Possibility 1: more dark matter in more massive galaxies
Possibility 2: bigger galaxies are older
Possibility 3: structure changes with size

Stellar populations of elliptical galaxies

The spectra of elliptical galaxies look, to first order, like G or K stars (with a few features of M stars).

This implies that they must be, on average, older than a few Gyr in order not to have light from hot stars.

Gas in elliptical galaxies

Some Elliptical galaxies contain HI, but nearly all contain a significant amount of hot X-ray gas.

~10–20% of the baryonic mass is in the form of gas at \(10^6–7\) K in a halo \(\geq 30\) kpc in radius.

Dark matter in elliptical galaxies

X-rays — hydrostatic equilibrium of hot gas gives a mass if the temperature and density structure are known: \(M/L_{2000} = 100\ M_\odot/L_\odot\) for \(r = 100\) kpc.

Careful modeling of kinematical data shows that many ellipticals have flat rotation curves.
Black holes in elliptical galaxies

If a super-massive black hole (SMBH) lives at the center of a galaxy, we should be able to detect this by looking at the speeds of stars that pass near to the black hole.

So we need to find stars that have speeds of

\[ V^2(r) \approx \frac{GM_{\text{BH}}}{r} \gtrsim \sigma_c^2 \]

This means we need to look within a radius

\[ r_{\text{BH}} \approx 45 \text{ pc} \left( \frac{M_{\text{BH}}}{10^8 M_\odot} \right) \left( \frac{\sigma_c}{100 \text{ km s}^{-1}} \right) \]

In M32, 2x10^4 M_\odot are required inside the central parsec!

Black holes in elliptical galaxies

Because \( M_{\text{bulge}} \sim \sigma^2 r \)
this implies a \( M_{\text{BH}} - M_{\text{bulge}} \) relation

\[ \frac{M_{\text{BH}}}{M_{\text{bulge}}} = 2.2^{+1.6}_{-0.9} \times 10^{-3} \]

In other words, the black hole at the center of a galaxy is \( \approx 0.2\% \) of the mass of its bulge!

Black holes in elliptical galaxies

It is likely that every elliptical galaxy — in fact, every spheroidal system, including bulges — has a super massive black hole (SMBH)

Moreover, there is a reasonable correlation between the mass of the SMBH and the velocity dispersion of the spheroid:

\[ \log(M_{\text{BH}}/M_\odot) = 4.24 \log(\sigma/200 \text{ km s}^{-1}) + 8.12 \]