Elliptical galaxies

•The brightest galaxies in the Universe are ellipticals, but also some of the faintest.

•Elliptical galaxies appear simple: roundish on the sky, the light is smoothly distributed, and they lack star formation patches or strong internal obscuration by dust.

•But are they so simple? Detailed studies reveal great complexity:

- •shapes (from oblate to triaxial);
- •large range of luminosity and light concentration;
- •fast and slowly rotating;
- •cuspy and cored …

Classification by luminosity

- There are three classes of ellipticals, according to their luminosity:
  - Giant ellipticals have $L > L_*$, where L_* is the luminosity of a large galaxy, $L_* = 2 \times 10^{10} L_\odot$ or $M_B = -20$ (the Milky Way is an L_* galaxy).
  - Midsized ellipticals are less luminous, with $L > 3 \times 10^9 L_\odot$, or $M_B < -18$
  - Dwarf ellipticals have luminosities $L < 3 \times 10^9 L_\odot$

- These luminosity classes also serve to describe other properties of E galaxies (in contrast to disk galaxies, where each class be it Sa … Sd contains a wide range of sizes and luminosities).

- Ellipticals come in one-size sequence: their internal properties are correlated with their total luminosity (or mass)

Galaxy photometry

The surface brightness of a galaxy I(**x**) is the amount of light on the sky at a particular point **x** on the image.

Consider a small patch of side D in a galaxy located at a distance d. It will subtend an angle $\alpha = D/d$ on the sky. If the combined luminosity of all the stars in this region is L, its apparent brightness is $F = L/(4\pi d^2)$.
Therefore the surface brightness

$$I(\mathbf{x}) = F/\alpha^2 = L/(4\pi\, d^2) * (d/D)^2 = L/(4\pi\, D^2).$$

The surface brightness is independent of distance (as long as the objects are not at cosmological distances, in which case the geometry of the Universe plays a role).

The appropriate units of I(x) are $L_\odot/pc^2$. However, quite often the magnitude is quoted instead of the flux at a given point on an image. In this case,
one also speaks of a surface brightness:

$$\mu_\lambda(x) = -2.5 \log_{10} I_\lambda(x) + cst_\lambda$$

The units of μ are [mag/arcsec^2.]

Galaxy photometry (cont)

The constant is set to have a value of 26.4 mag/arcsec^2 in the V-band. This magnitude corresponds to 1 $L_{\odot V}$/pc^2. Therefore, $I_V = 10^{0.4\,(26.4\,-\,\mu_V)}\ L_{\odot V}/\mathrm{pc}^2$

The total (apparent) magnitude of the galaxy is simply:

$$m = -2.5 \log_{10} \int d\phi\, R\, dR\, I(R,\phi)\ +\ cst$$

which for a circularly symmetric galaxy, reduces to

$$m = -2.5 \log_{10}\{2\pi \int R\, dR\, I(R)\}\ +\ cst$$

Given that galaxies have no sharp edges, it is customary to measure integrated magnitudes up to the radius of a given magnitude, usually 26 μ_B.

Note that usually I(R) will be given in units of energy/sec/arcsec^2, so that R is given in arcsec. Only if the distance to the object were known, could we derive its absolute magnitude.

Contours of constant surface brightness on a galaxy image are known as *isophotes*.

Surface brightness profiles of elliptical galaxies

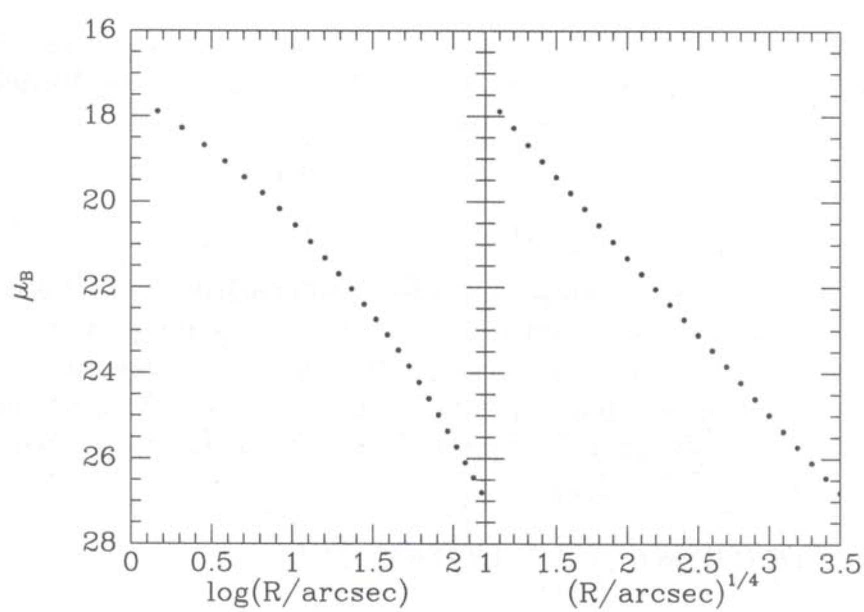
The quantity I(R) denotes the surface brightness profile on the major axis of an image.

The figure shows the surface brightness profile of the giant elliptical galaxy NGC 1700 as function of the projected distance to the center R (left) and as function of $R^{1/4}$ (right).

An $R^{1/4}$ profile is a straight line in this diagram. Note that it fits the data very well over 2 decades in radius.

The surface brightness falls 9 magnitudes from the centre to the outskirts, implying a 10^9 fall-off in projected luminosity!

The light in elliptical galaxies is quite centrally concentrated.



De Vaucouleurs profile

The light distribution of NGC 1700 can be fitted with a function which can be conveniently written as:

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

with
- R_e the ***effective radius***
- the factor 3.33 is included so that half of the total light is emitted inside a radius R_e
- the parameter I_e is the surface brightness at $R = R_e$
- the central brightness of the galaxy is $I_0 \sim 2000\, I_e$.

It is remarkable that such a simple 2-parameter profile, can fit the profiles of ellipticals so well.

This profile is a particularly good description of the surface brightness of giant and midsized elliptical galaxies.

Other common profiles

Sersic law: $$I(R) = I_e 10^{\{-b_n[(R/R_e)^{1/n}-1]\}}$$

where 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.
Dwarf ellipticals are better fit by exponential profiles.

Hubble-Oemler law:

$$I(R) = \frac{I_0 \mathrm{e}^{-R^2/R_t^2}}{(1 + R/r_0)^2}$$

with I_0 the central surface brightness, and r_0 the radius interior to which the surface brightness profile is approx. constant.
For $r_0 < R < R_t$ the surface brightness changes as $I \sim R^{-2}$.
For $R > R_t$ the surface brightness profile decays very quickly and predicts a finite total luminosity.

In the limit $R_t \rightarrow \infty$ this one reduces to the ***Hubble law***: $$I(R) = \frac{I_0}{(1 + R/r_0)^2}$$

Central regions: the effect of seeing

The observed profile for NGC 1700 and other giant E follow rather closely de Vaucouleurs profiles, except in the very bright core, where atmospheric turbulence or seeing, blurs the image.

At small radii, the light is suppressed and redistributed at large radii.

Therefore seeing transforms a power-law profile into a profile with a ***core*** (a central region with nearly constant surface brightness).

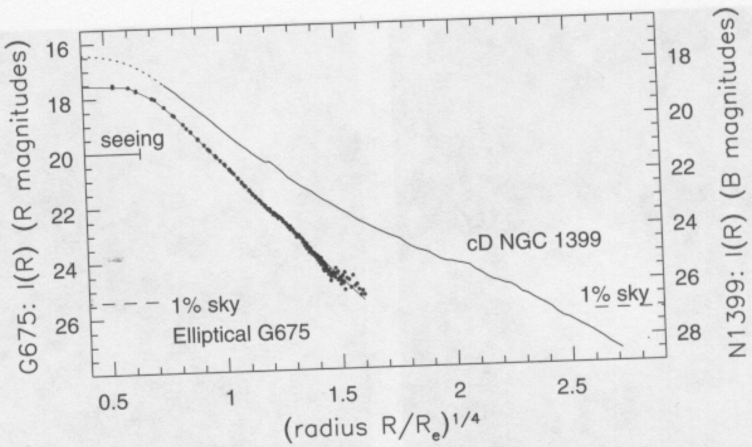


Figure 6.3 Surface brightness of two luminous ellipticals: an $R^{1/4}$ law corresponds to a straight line. Dots show the measured R-band surface brightness for galaxy G675, in cluster Abell 2572. It has $L_V \approx 2 \times 10^{10} L_\odot$, and $R_e = 4.95''$ or 3.8 kpc. The curve gives an $R^{1/4}$ profile, smoothed by atmospheric seeing: the horizontal bar shows 1.67″, the half-width of a stellar image. The upper curve shows the measured B-band profile of the cD galaxy NGC 1399, about twice as luminous as G675. For it, $R_e = 15.7'' \approx 1.4$ kpc, so measurements cover $R \lesssim 850''$ or 75 kpc. Between the dotted region where seeing has affected the measurement, and $R \sim 2^4 R_e$, $I(R)$ follows the $R^{1/4}$ profile closely – R. Saglia, N. Caon.

Due to seeing, stars are not observed as point sources but have finite extent. Their light-profile can often be expressed as a Gaussian with a characteristic extent, quantified by the dispersion σ, or half-peak intensity radius. This is known as the PSF: Point Spread Function.

Effect of Seeing - PSF

The effect of the seeing is to ***blur*** an otherwise sharp image. If in absence of seeing the surface brightness of an object at a position **R'** is I_t(**R'**), the measured brightness at a location **R** will be:

$$I_{\mathrm{app}}(\mathbf{R}) = \int d^2R' P(\mathbf{R} - \mathbf{R}') I_t(\mathbf{R}')$$

where P(**d**) is the PSF. Note that in the absence of seeing, P would be the Dirac delta-function δ(**R – R'**), and one recovers the original (true) profile.

In the simplest case, the PSF can be treated as a circularly symmetric Gaussian

$$P(d) = \frac{1}{2\pi\sigma^2} e^{-d^2/2\sigma^2}$$

It is then possible to show that, for a circularly symmetric surface brightness distribution $I_t(R')$:

$$I_{\mathrm{app}}(R) = \int_0^{\infty} dR'\, R'\, I_t(R')\, I_0(\frac{RR'}{\sigma^2})$$

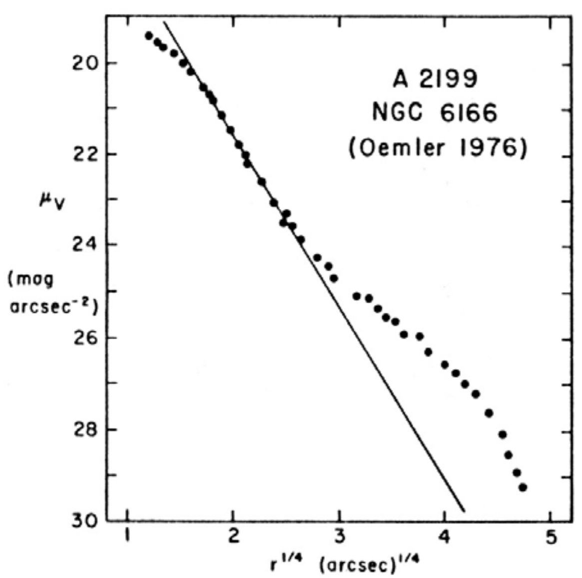
where I_0 is the modified Bessel function of order 0.

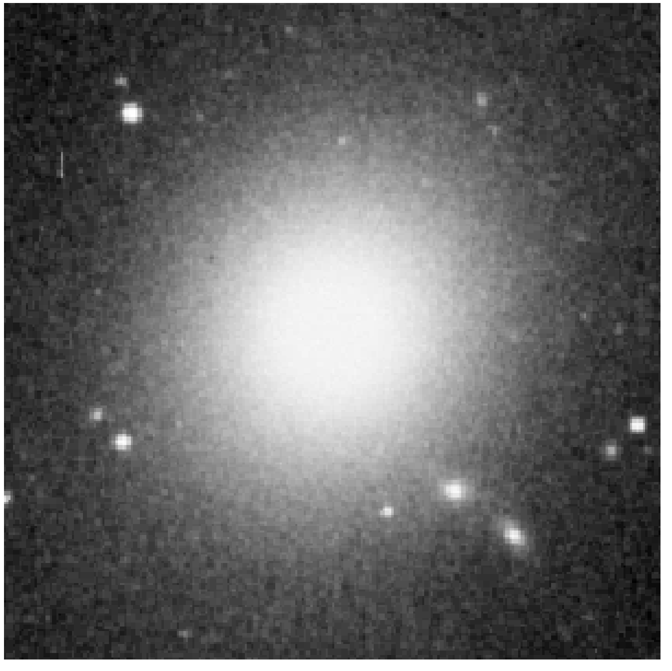
The outskirts of galaxies

•The surface brightness profile of giant ellipticals often shows an excess of light in the outer parts compared to the de Vaucouleurs profile.

•Such galaxies are known as ***cD Galaxies***. They are usually located at the center of clusters of galaxies, or in areas with a dense population of galaxies.

•This excess emission indicates the presence of an extended halo. The cD halos could belong to the cluster rather than to the galaxy.





M87, the central cD galaxy in the clusters of galaxies inVirgo. Note the extended, low-surface brightness halo.

Photometric properties of E galaxies

•The central surface brightness of an elliptical is tightly correlated with the total luminosity.

•The plot shows the central brightness $I_V(0)$, the core radius r_c (the radius at which the surface brightness has dropped to half its central value) as functions of the total luminosity or absolute magnitude

•Note that for the giant and midsized E, the more luminous the galaxy, the lower its central brightness, and the larger its core.

•This shows, that just like with stars, the properties of galaxies are not random: there is a certain degree of coherence.

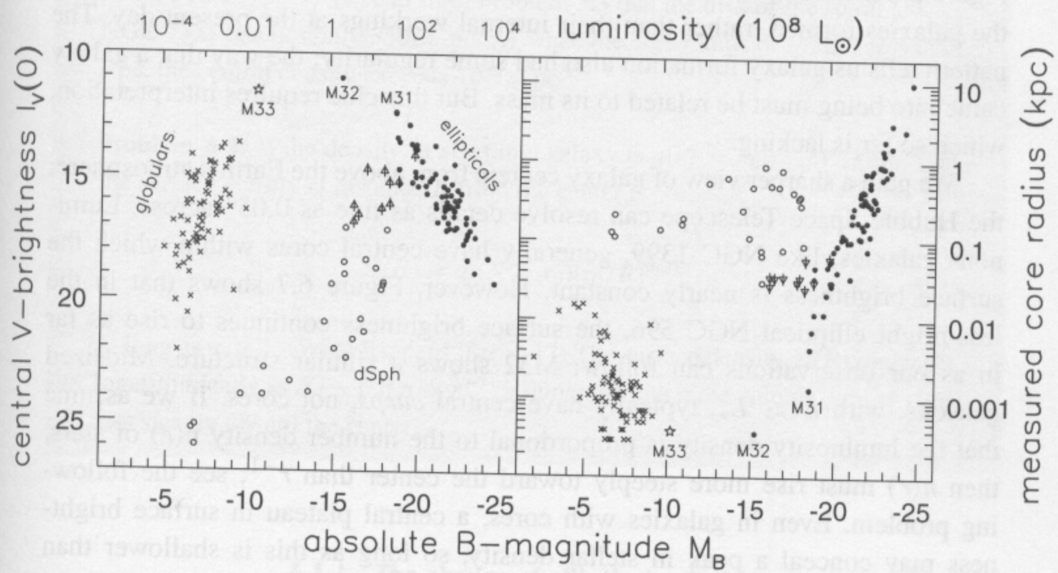


Figure 6.6 Central surface brightness $I_V(0)$ in mag arcsec^{-2} in the V band, and core radius r_c, measured from the ground, plotted against B-band luminosity M_B. Filled circles are elliptical galaxies and bulges of spirals (including the Andromeda galaxy M31); open circles are dwarf spheroidals; crosses are globular clusters; the star is the nucleus of Sc galaxy M33. Arrows show ellipticals in the Virgo cluster; here, seeing may cause us to measure too low a central brightness, and too large a core – J. Kormendy.

Cores and cusps

•Space observations, where seeing does not play any role, show that midsized galaxies have central cusps, and not cores.

•The measured central surface brightness from the ground is therefore, only a lower bound to the true value.

•The "core radius" does not always have the same physical meaning: it could be a point where the brightness profile changes slope, rather than the outer limit of a region where the stellar surface brightness is constant.

•Midsize ellipticals are usually cuspy, while giant ellipticals tend to have cores

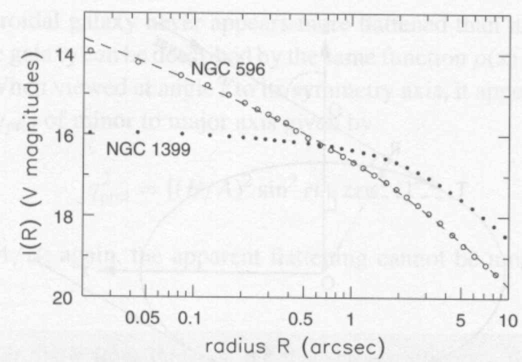


Figure 6.7 Surface brightness $I_V(R)$ in the V-band at the centers of two elliptical galaxies. The cD galaxy NGC 1399 ($M_V = -21.7$) has a *core* at $R \lesssim 1''$, where $I(R)$ is nearly constant. NGC 596 ($M_V = -20.9$) is half as luminous; the surface brightness continues to rise as a *cusp*. The dashed line shows $I(R) \propto R^{-0.55}$ – T. Lauer.

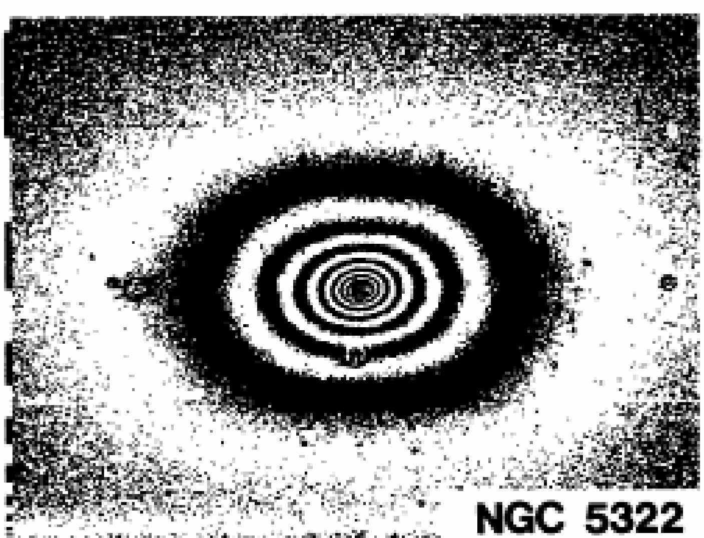
Isophotes

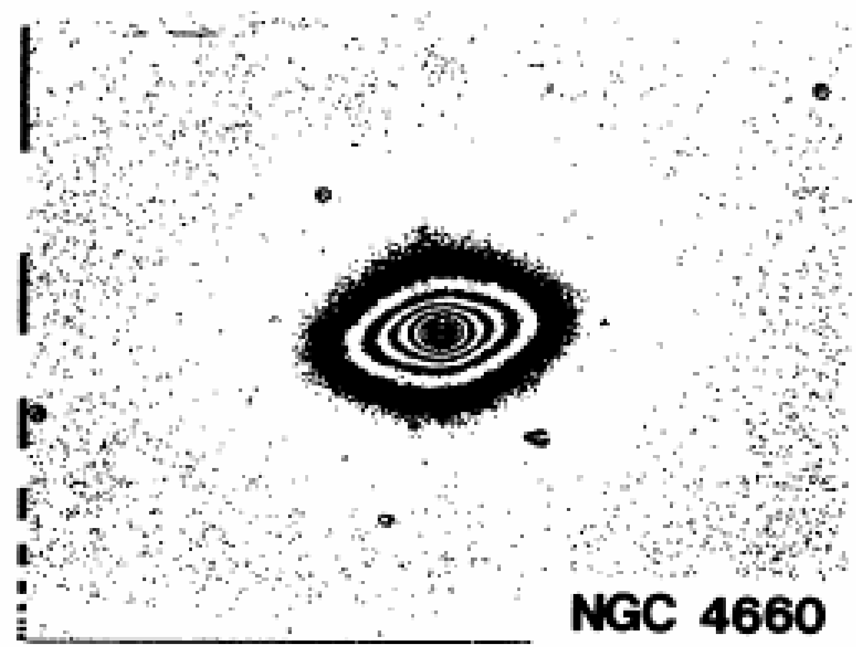
•Isophotes are contours of constant surface brightness.

•The ratio of semi-major to semi-minor axis measures how far the isophote deviates from a circle $\varepsilon = 1 - b/a$.

•This allows to classify E galaxies by type En, where $n = 10\ (1-b/a)$

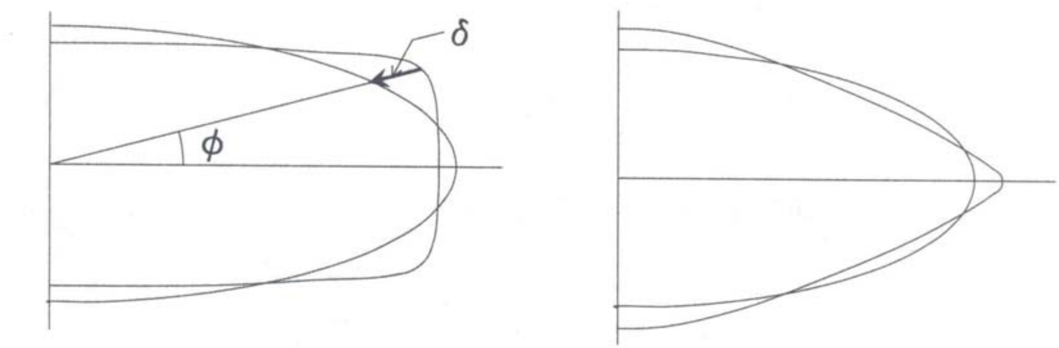
•Note that this classification depends strongly on viewing angle





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

$$\delta(\phi) = \langle\delta\rangle + \Sigma\, a_n \cos n\phi + \Sigma\, b_n \sin n\phi$$

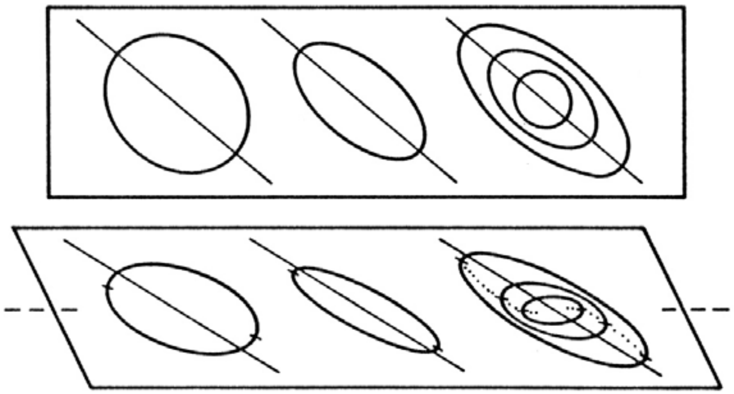
•If the isophotes have 4-fold symmetry, and the ellipse has been correctly fitted, then terms with $n < 4$ and all b_n should be small. The value of a_4 tells us the shape:

- •$a_4 > 0$ is a disky E,
- •$a_4 < 0$ corresponds to a boxy E.

Isophote twisting

In the case the true intrinsic shape of a galaxy is triaxial, the orientation in the sky of the projected ellipses will not only depend upon the inclination of the body, but also upon the body's true axis ratio.

This is best seen in the projection of the following 2-D figure:

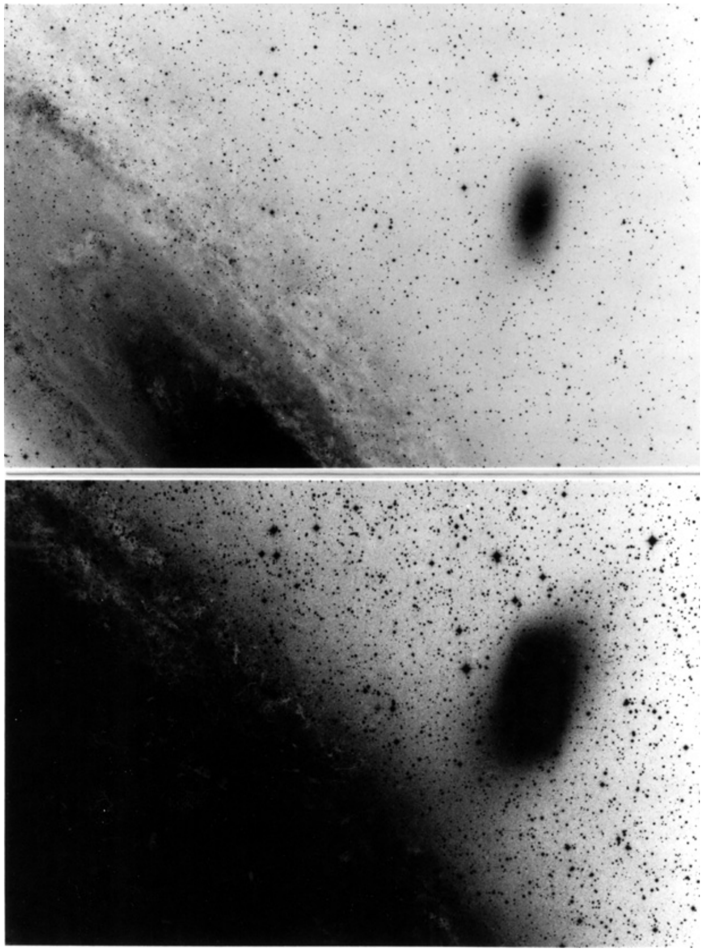


Since the ellipticity changes with radius, even if the major axis of all the ellipses have the same orientation, they appear as if they were rotated in the projected image.

This is called ***isophote twisting***.

Unfortunately it is impossible, from an observation of a twisted set of isophotes, to conclude whether there is a real twist, or whether the object is triaxial.

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



The first, shallower, exposure shows the brightest part of the galaxy. The second, deeper, exposure shows the weaker more extended emission. A twist between both images of the same galaxy are apparent (the orientation in the sky is the same in both figures).

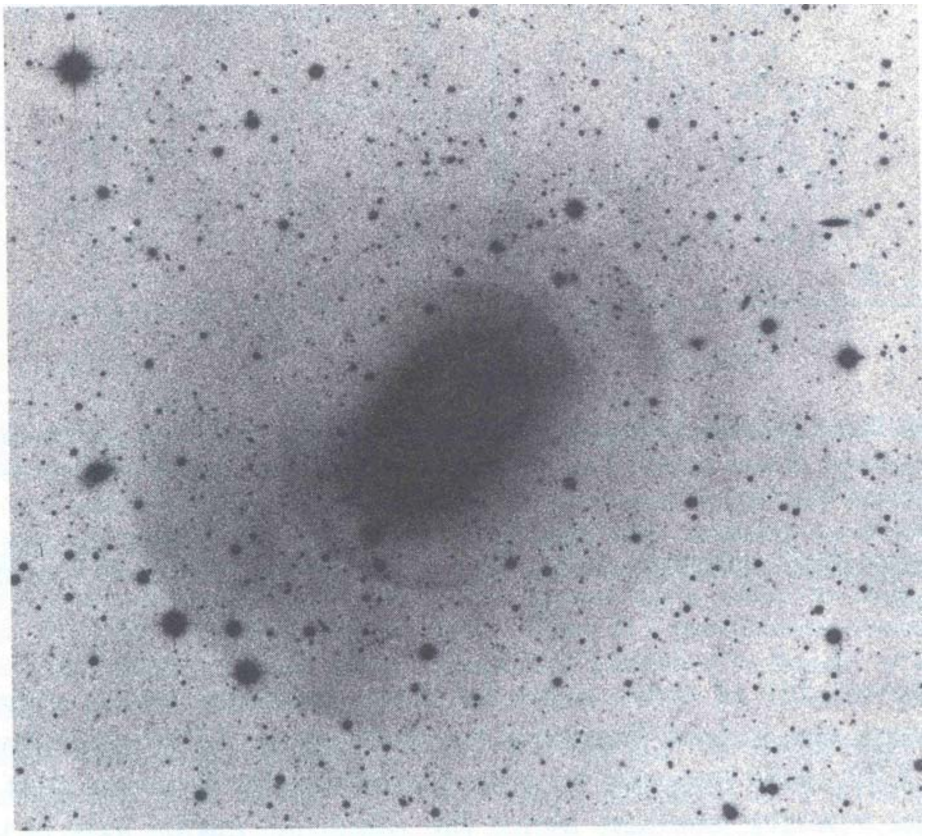
- Boxy galaxies are
  - more likely to show isophote twists,
  - more luminous in general,
  - probably triaxial.

- Disky E are
  - midsize,
  - more often oblate,
  - and faster rotators.

Some people have suggested disky E can be considered an intermediate class between the big boxy ones and the S0s.

Fine structure

About 10 to 20% of the elliptical galaxies seem to contain sharp steps in their luminosity profiles. An example is the elliptical NGC 3923:



These features are called ***ripples and shells.***

Ripples and shells have also been detected in S0 and Sa galaxies.

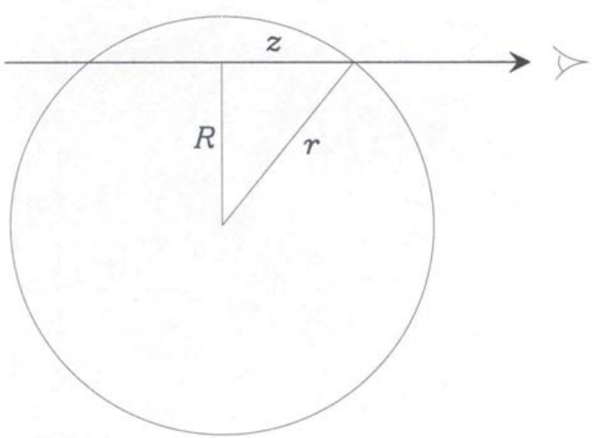
Since in early-type galaxies they are detected because of the smooth profile of the underlying galaxy, it is not clear whether this is an universal phenomenon also present in later-type galaxies but difficult to detect there.

They are probably the result of the accretion/merger of a small galaxy on a very elongated (radial) orbit (Quinn 1984).

De-projection of galaxy profiles

So far we have discussed observed surface brightness profiles $I(\mathbf{R})$, that is 3-dimensional distribution of light projected onto the plane of the sky.

The question is whether we can, from this measured quantity, infer the true 3–D distribution of light, $j(\mathbf{r})$ of the galaxy. If $I(\mathbf{R})$ is circularly symmetric, it is possible that $j(\mathbf{r})$ is spherically symmetric, and from the following figure it is apparent that:



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

De-projection: Abel integral

This is an Abel integral equation for j as a function of I, and its solution is:

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

An example of a simple pair (connected via the Abel integral), that approximately represents the profiles of some elliptical galaxies, is:

$$I(R) = \frac{I_0}{1 + (R/r_0)^2} \longleftrightarrow j(r) = \frac{j_0}{[1 + (r/r_0)^2]^{3/2}}$$

This surface brightness profile is known as the ***modified Hubble law***. Notice that for R >> r_0: $I \sim R^{-2}$, and $j \sim r^{-3}$.

De-projection: Non-spherical case

•If the isophotes are not circularly symmetric, then the galaxy cannot be spherically symmetric, but it can still be axisymmetric.

•In that case, if the observer looks along the equatorial plane of such object, it can be shown that is still possible to de-project the surface density profile and obtain the spatial profile.

•However, in general the line of sight will be inclined at an angle with respect to the equatorial plane of an axisymmetric galaxy.

•In that case it can be shown that there are infinite de-projected profiles that match an observation.

•It is easy to see that when observed from the pole, both a spherical galaxy as well as any oblate or prolate ellipsoid will produce the same projected distribution (as long as the 3-D radial profile is properly constructed).

Shapes of elliptical galaxies

What can we learn from the distribution of observed apparent ellipticities about the true (intrinsic) distribution of axis ratios?

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

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

The contours of constant density are ellipsoids of $m^2 = \text{constant}$.

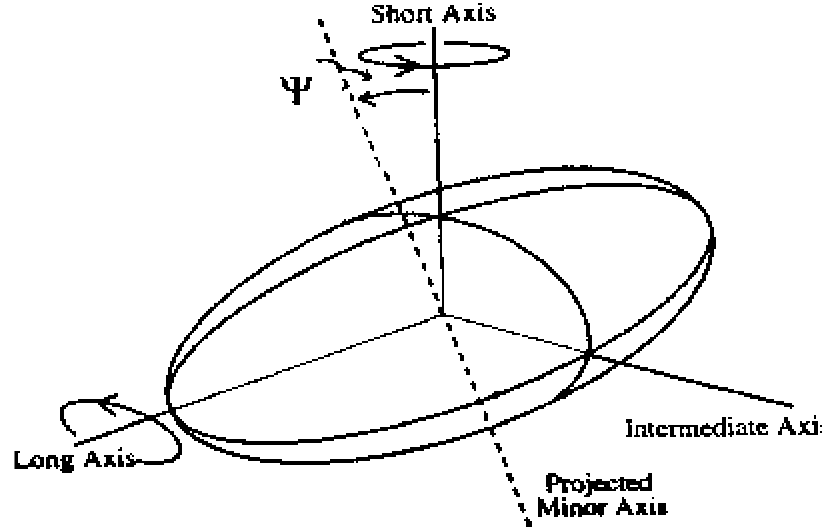


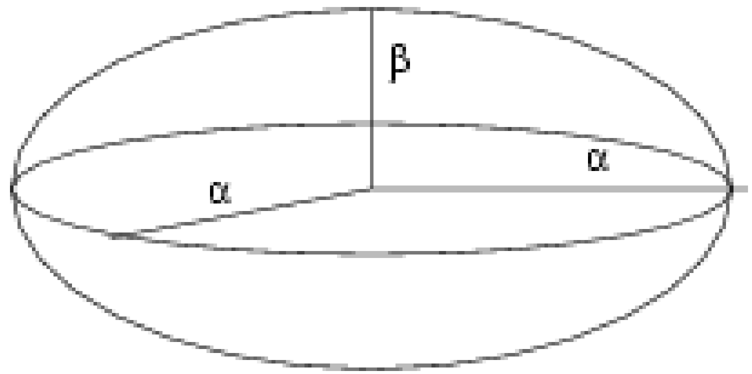
Figure 2.2: *The projection of a Prolate-Triaxial model*

There are three cases:

$\alpha \neq \gamma \neq \beta$: triaxial
$\alpha = \gamma < \beta$: prolate (cigar-shaped)
$\alpha = \gamma > \beta$: oblate (rugby-ball)

Shapes of elliptical galaxies

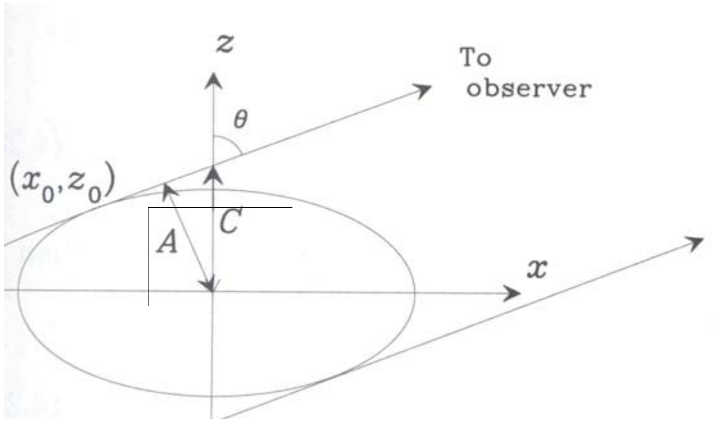
Let's assume that an elliptical galaxy is an oblate spheroid.



An observer looking down the z-axis will see an E0 galaxy, while
when viewed at an angle, the system will look elliptical, with axis ratio $q_0 = b/a$.

How is q_0 related to α and β ?

Apparent axis ratios



The observed axis ratio is $q_0 = A/(m\ \alpha)$.

The line of sight intersects the ellipsoid at (x_0, z_0) at the constant-density surface m.

The segment $A = C \sin\theta$, while $C = z_0 + (-\ x_0)/\tan\theta$; and $\tan\theta = dx/dz$.

Differentiating $d(m^2 = x^2/\alpha^2 + z^2/\beta^2) = 0$, we find $\tan\theta = -z_0/x_0\ \alpha^2/\beta^2$.

Replacing, $C = m^2\ \beta^2 / z_0$. Finally $q_0 = m\ \beta^2 / (\alpha\ z_0) \sin\theta$, or

$$q_0^2 = \cos^2\theta + (\beta/\alpha)^2 \sin^2\theta$$

This implies that the apparent axis ratio is always larger than the true axis ratio, a galaxy never appears more flattened than it actually is.

Expectations

We can use the previous relation to find the distribution of apparent ellipticities q_0 produced by a random distribution of oblate/prolate ellipsoids with axis ratios $q = \beta/\alpha$.

If the ellipsoids are randomly oriented wrt line-of-sight with angle θ, then of the $N(q)\,dq$ galaxies with true axis ratio in the interval $(q, q + dq)$, a fraction $\sin\theta\, d\theta$ will be inclined with their axis in $(\theta, \theta + d\theta)$.

The probability, $P(q_0|q)\, dq_0$, to observe a galaxy with true axis ratio q to have apparent axis ratio between q_0 and $q_0 + dq_0$ is:
$P(q_0|q)\, dq_0 = \sin\theta\, d\theta$ thus $P(q_0|q) = \sin\theta / |\, dq_0/d\theta\,|$.
(where $q_0 = q_0\,(\theta)$ is known)

If there are $f(q_0)dq_0$ galaxies with (observed) axis ratios in $(q_0, q_0 + dq_0)$, then

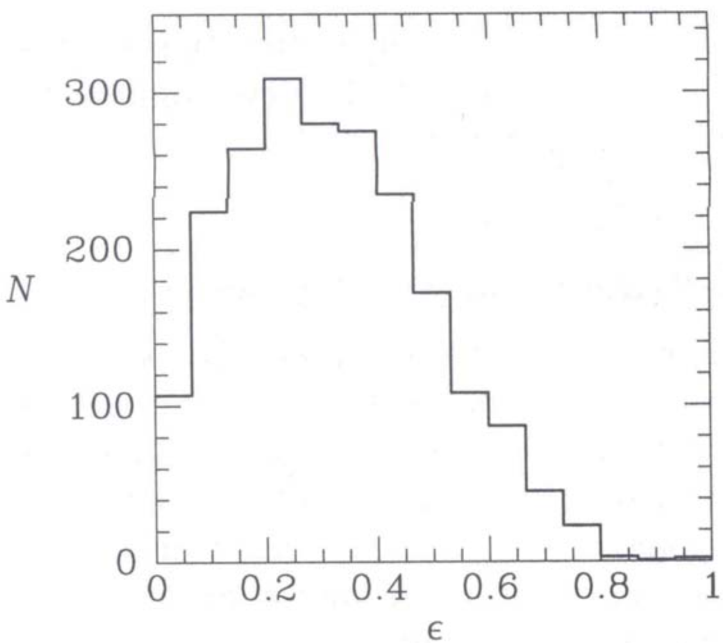
$$f(q_0)dq_0 = N(q)\, dq\; P(q_0|q)\, dq_0\ .$$

Distribution of ellipticities

We have then that

$$f(q_0) = \int N(q)\,dq\,P(q_0 \mid q) = q_0 \int \frac{N(q)\,dq}{\sqrt{1-q^2}\sqrt{q_0^{\;2} - q^2}}$$

This is an integral equation for N(q), which can in principle be solved from the observed distribution of ellipticities.



This is the observed distribution of apparent ellipticities ($\varepsilon = 1 - q_0$), for 2135 E galaxies

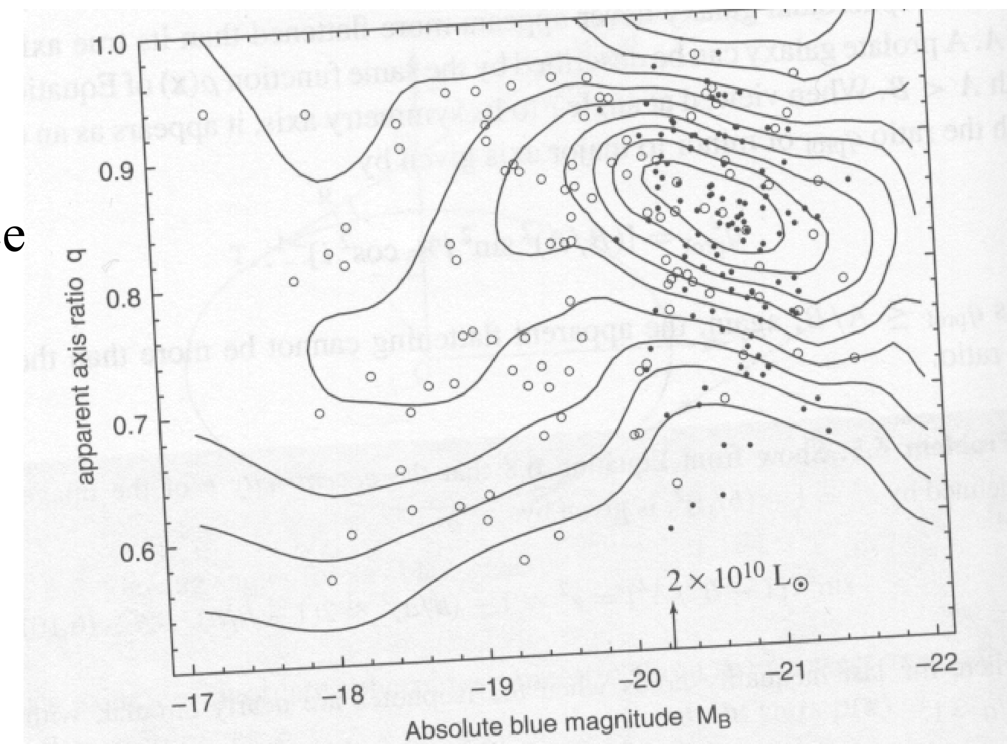
Conclusion: It is not possible to reproduce the observed distribution if all galaxies are either prolate or oblate axisymmetrical ellipsoids.

More on shapes

•The apparent shapes of small E are more elongated than for large E

•On average, midsized ellipticals (M > -20), have $q_0 \sim 0.75$. If they are oblate, this would correspond to $0.55 < q < 0.7$

•Very luminous E, with M < -20, have on average $q_0 \sim 0.85$. But since there are so few that are spherical on the sky, it is very likely that most of these are actually triaxial.

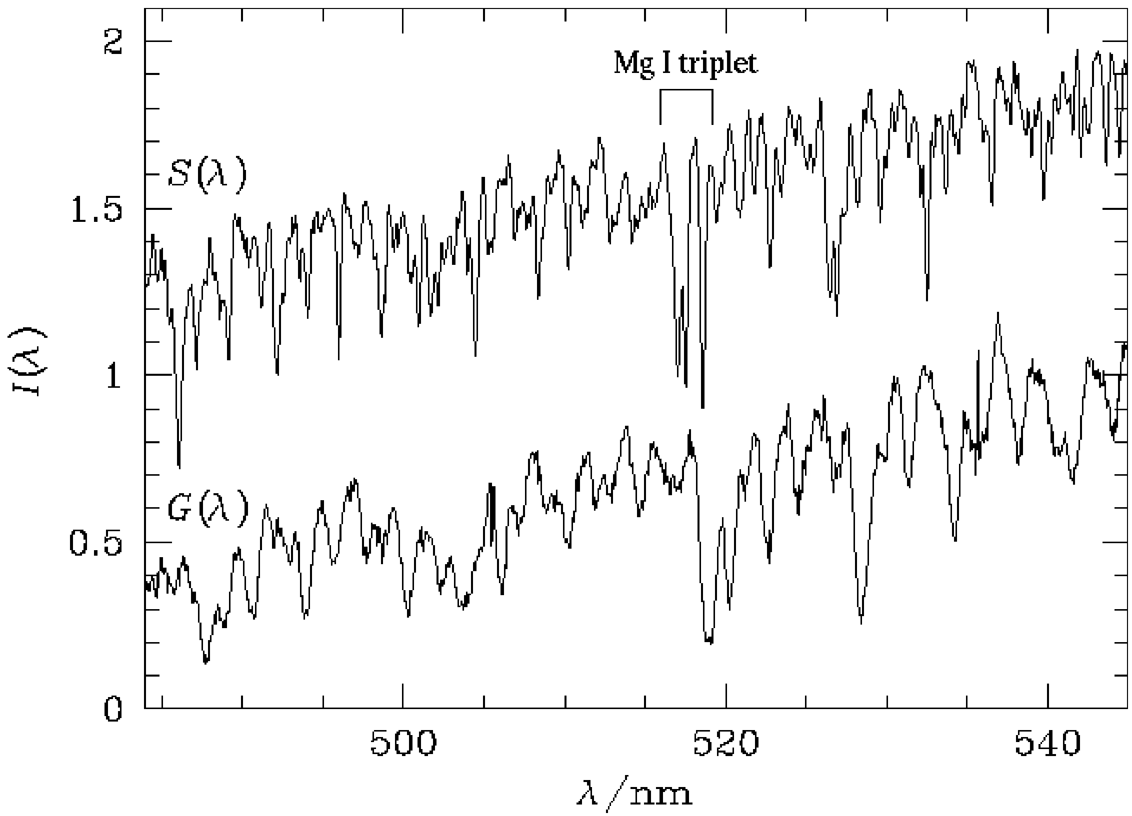


The kinematics of stars in E galaxies

Stars in E galaxies do not follow ordered motions, but most of their kinetic energy is in the form of random motions. Moreover, the more luminous an E, the larger the velocity dispersion (which, as we have seen can be used to derive distances to E).

To measure the orbital velocities of stars within galaxies is a difficult task.

Absorption lines are used, which are the result of the light of all stars. Each star emits a spectrum which is Doppler shifted in wavelength according to its motion. This orbital motion makes the resulting spectral lines be wider than those of an individual star.



Spectra and motions of stars in E

Let the energy received from a typical star, at rest with respect to the observer, be $F(\lambda)\ \Delta\lambda$. If the star moves away from us with a velocity $v_z \ll c$, the light we receive at wavelength λ, was emitted at $\lambda\ (1 - v_z/c)$.

To find the spectrum on the galaxy image, one needs to integrate over all stars along the line of sight (z-direction). If the number density of stars at position **r** with velocities in $(v_z, v_z + dv_z)$ is $f(\mathbf{r}, v_z)dv_z$, the observed spectrum is

$$F_{gal}(x, y, \lambda) = \int_{-\infty}^{\infty} d\mathrm{v}_z\ \mathrm{F}(\lambda[1 - \mathrm{v}_z / c]) \int_{-\infty}^{\infty} dz\ \mathrm{f}(\mathrm{r}, \mathrm{v}_z)$$

If the distribution function $f\,(\mathbf{r}, \mathbf{v})$ was known, and the spectra were the same for all stars, we could derive the spectrum of the galaxy. In practice, one makes a guess for the $f(\mathbf{r}, v_z)$, which depends on a few parameters, and fixes those in order to reproduce the observed spectrum.

Spectra and motions of stars in E

A common choice is the Gaussian: $$\int_{-\infty}^{\infty} \mathrm{f}(\mathrm{r}, \mathrm{v_z})dz \propto \exp[-(\mathrm{v_z} - V_r)^2 / 2\sigma^2]$$

where $\sigma(x,y)$ is the velocity dispersion of stars, while $V_r(x,y)$ is the mean radial velocity at that position.

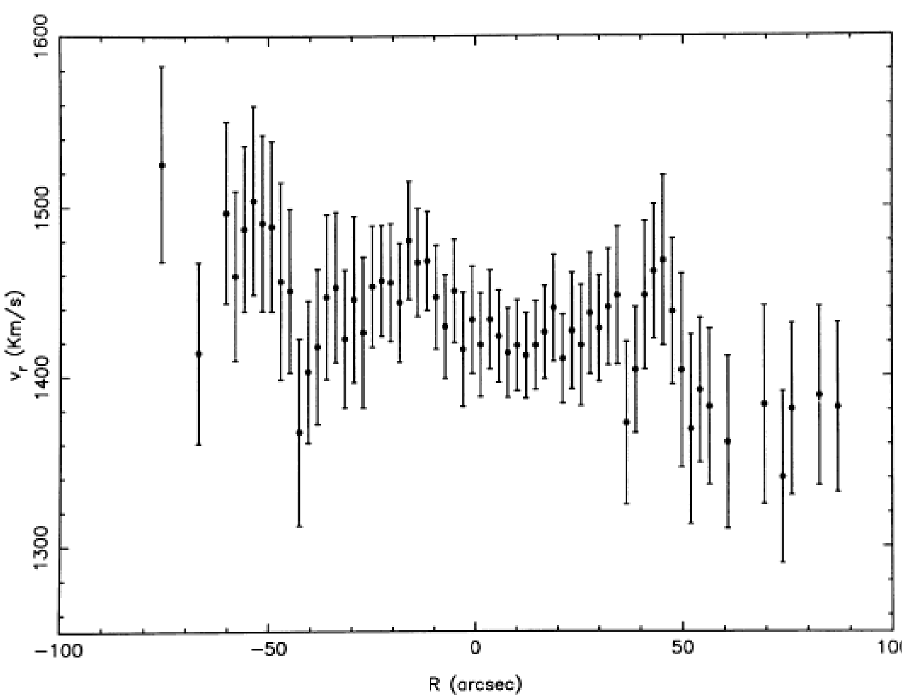


FIG. 2.—The rotation curve of NGC 1399

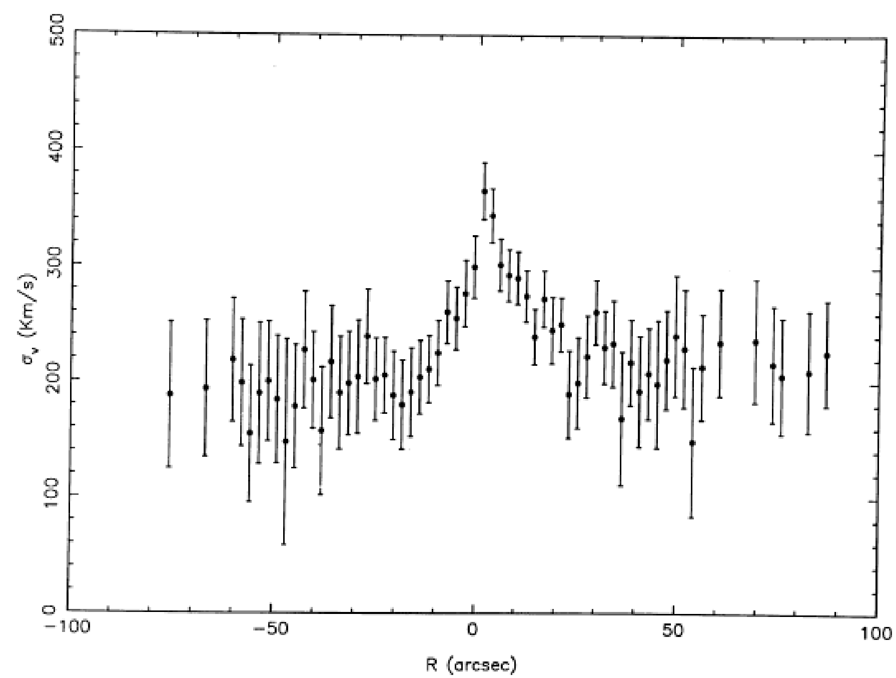
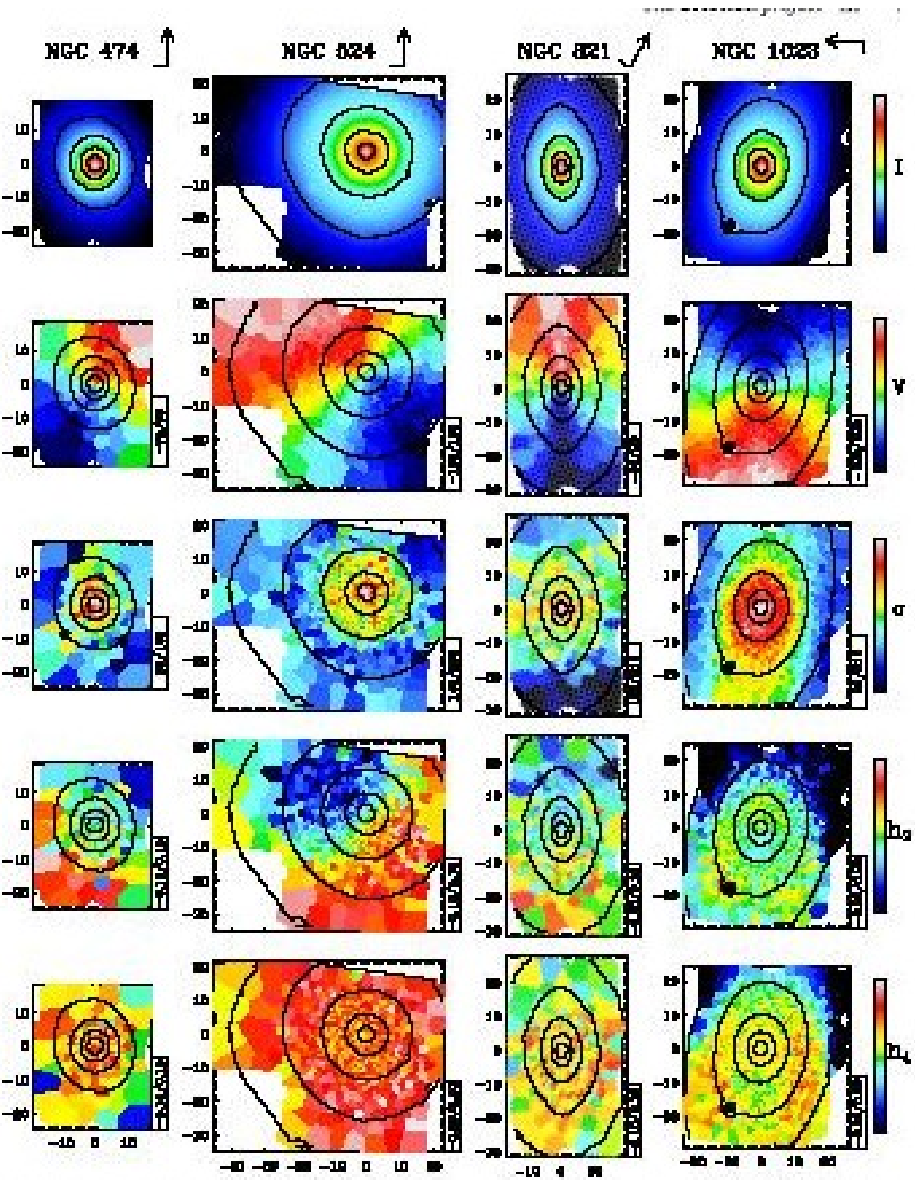


FIG. 3.—The velocity dispersion profile of NGC 1399. East is to the left, and west is to the right.

2D-maps of the kinematics



It has recently become possible to take multiple spectra over the image of a galaxy. This is known as integral field spectroscopy. Each pixel in the image has a corresponding spectrum.

This is an example from the SAURON team for 4 elliptical galaxies.

It is now possible to see how the velocity field and its higher moments vary across the galaxy, and to find departures from axial symmetry.

This study has shown that E galaxies are far less regular than originally believed. One finds counter-rotating cores, misalignments, minor axis rotation…

Do Elliptical galaxies rotate?

It was initially thought that the flattened shape of some E galaxies was due to them being fast rotators. However, observations have shown that

- Bright ellipticals (boxy) rotate very slowly, particularly in comparison to their random motions. Their velocity ellipsoids must be anisotropic to support their shapes.

- Midsized ellipticals (disky) seem to be fast rotators

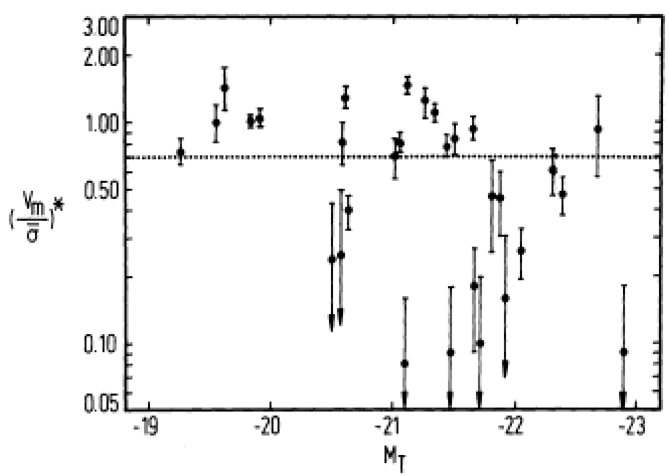


Fig.2: The anisotropies $(v_m/\bar{\sigma})^*$ against the absolute magnitudes M_T of elliptical galaxies. Galaxies with $(v_m/\bar{\sigma})^* \lesssim 0.7$ most certainly have anisotropic velocity dispersions.

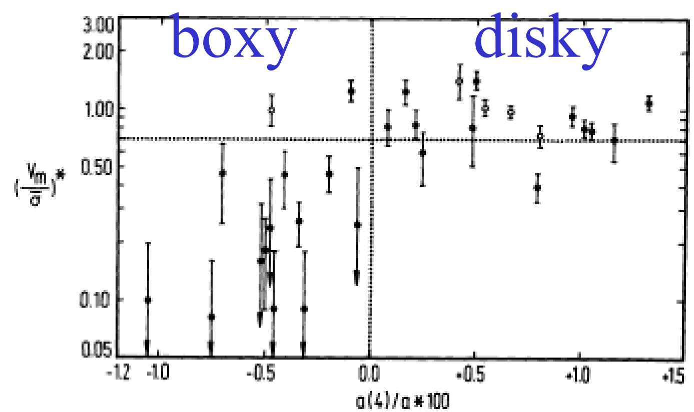


Fig.3: The anisotropies $(v_m/\bar{\sigma})^*$ in elliptical galaxies against their isophote parameters a(4)/a. Positive a(4)/a indicate peaked isophotes most probably caused by weak disk components, negative a(4)/a describe box-shaped isophotes. Weak ellipticals (M_T > -20.5) are denoted by open circles, luminous ellipticals (M_T < -20.5) by filled circles .

Link between shape and internal kinematics

In the case of a star like the Sun, the frequent random encounters between gas particles produces a round smooth sphere. When this sphere is given some angular momentum, it will change its shape and become more flattened near the poles.

In the case of E galaxies, we know that collisions play no role (timescales are much larger than a Hubble time). So the argument that their flattened shape of some E galaxies would be due to rotation is flawed.

However, one still expects to find a correlation between the shape of a galaxy and the degree of anisotropy (rotation + random motions) of the velocities of the stars.

For example, if a system is very flattened in one direction, this means that the velocities of the stars along that direction (or axis) must be smaller than those along a perpendicular direction (otherwise they would reach larger distances and lead to a rounder shape).

This is why the internal kinematics of the stars (i.e. velocity anisotropy) will be related to the intrinsic shape of a Galaxy.

Scaling relations for E galaxies

We have seen before that E galaxies follow the Faber-Jackson relation

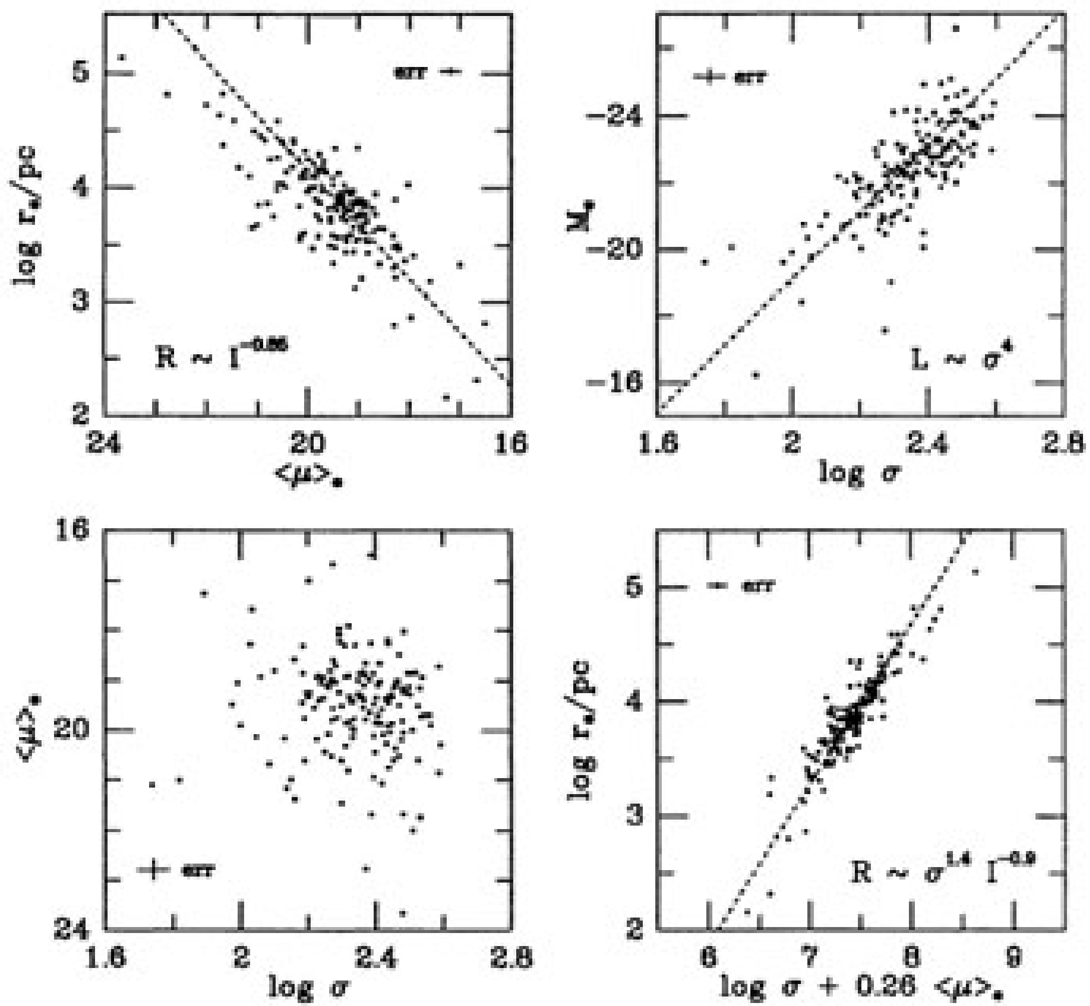
$$L_V \approx 2\times10^{10} L_{sun} \left(\frac{\sigma}{200\,\mathrm{km/s}} \right)^4$$

which can be used to derive distance to a galaxy. Note that this relation implies that more luminous galaxies have larger velocity dispersions (the typical range is from 50 km/s for dE up to 500 km/s for the brightest Es).

Another scaling relation E galaxies follow is the fundamental plane. Elliptical galaxies all lie close to a plane in the 3D space defined by (velocity dispersion σ, effective radius R_e, surface brightness I_e). Approximately

$$R_e \propto \sigma^{1.24} I_e^{-0.82}$$

The fundamental plane



Kormendy & Djorgovski 1989

These plots show some of the scaling relations that E galaxies satisfy.

They are all projections of the fundamental plane relation, that is shown in the last panel.

They express some fundamental property of E galaxies.

We will show in an exercise that the such correlations are not surprising if one uses the virial theorem

Stellar populations in E galaxies

It is not possible to see individual stars in galaxies beyond 10-20 Mpc.

Hence the stellar populations characteristics of E galaxies must be derived from the integrated colours and spectra.

As we saw before, the spectrum of an E galaxy resembles that of a K giant star.

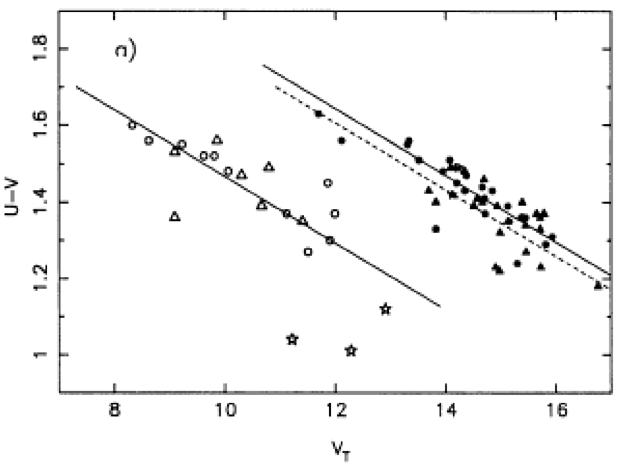
E galaxies appear generally red:

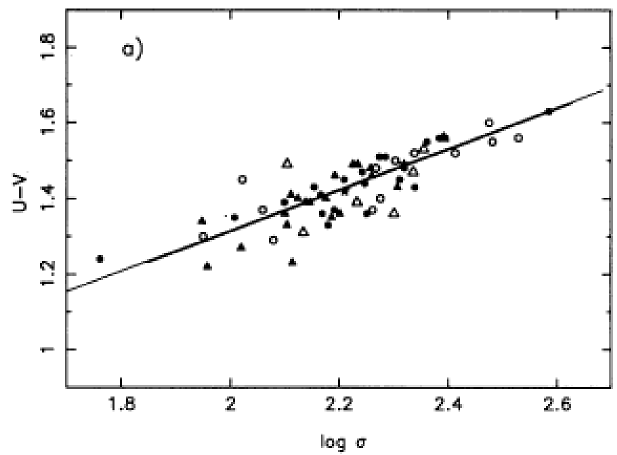
- very few stars made in the last 1-2 Gyr (recall that after 1 Gyr, only stars with masses $< 2\ M_\odot$ are still on the main sequence)
- Most of the light is emitted while stars are on the giant branch
- The stars in the centres of E are very metal-rich, similar to the Sun

This would seem to suggest that E galaxies are very old

CMDs for E galaxies

There is a relation between the colour, and total luminosity for E galaxies.





Sandage 1972

These plots show, for galaxies in the Coma and Virgo clusters, that

- Brighter galaxies are redder
- Fainter systems are bluer

This could be explained if small E galaxies were younger or more metal-poor than the large bright ones. The fact that metallicity can mimic age effects, prevents one from concluding which of the two cases (or both) is closer to the truth (without resolved deep colour-magnitude diagrams it is not possible to solve this problem)

•We understand why stars occupy certain regions of the color-magnitude diagram: the luminosity and temperature are controlled by the stars mass, and the nuclear processes occurring inside the stars.

•Explaining the correlations in the properties of E galaxies is harder, because they almost certainly reflect the conditions under which the galaxies formed, rather than their internal workings at the present day. The well-defined patterns tell us that galaxy formation also had some regularity, and that the process must somehow be related to its mass.

Gas in E galaxies

The lack of young stars in E galaxies is not surprising given that most contain very little cool gas.

Roughly 5 - 10 % of normal ellipticals contain HI or molecular gas to be detectable (for the big elliptical galaxies this is less than 10^8 - 10^9 $M_\odot$. This should be compared to a large Sc which has 10^{10} $M_\odot$).

There are some exceptions, but are usually peculiar (i.e. dust lanes, recent merger, etc).

However, the average elliptical contains very large amounts of hot ionized gas.
This gas

- emits in X-rays ($T \sim 10^7$ K)
- located in a halo of ~ 30 kpc radius
- roughly 10 - 20% of the mass in stars is in this component

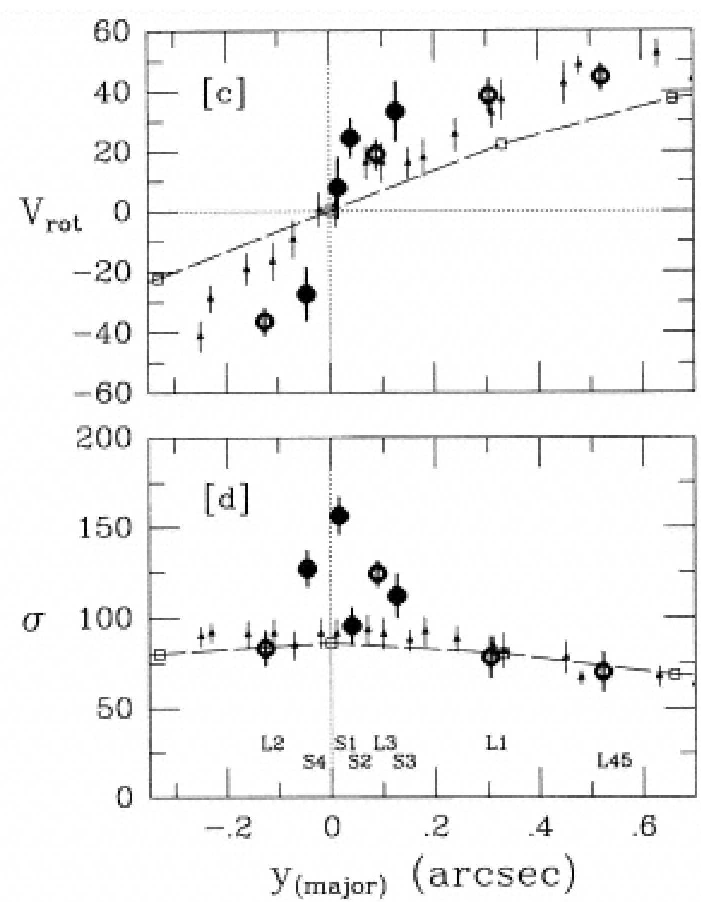
Boxy ellipticals tend to have more luminous X-ray halos and are also radio-loud (i.e. they emit in the radio wavebands).

Black holes in the centres of E

Some E galaxies have rising velocity dispersions as one moves closer to the centres. To keep fast moving stars within the centres, requires large masses concentrated in small regions of space, beyond what can be accounted for by the stars themselves.

For example, for M32, a dwarf E satellite of M31, 2 million solar masses needed within the central 1 parsec!!

The current preferred explanation is that these large masses are actually due to super-massive black holes. Some believe that every galaxy harbours a SMBH.



Black holes in the centres of E

There is some evidence that the mass of the SMBH correlates with the total luminosity or velocity dispersi

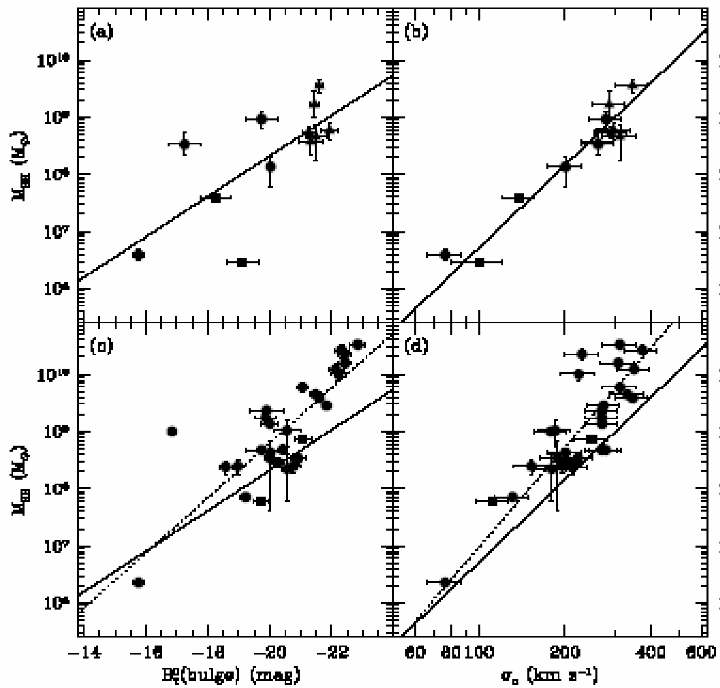


FIG. 1.— (a): BH mass versus absolute blue luminosity of the host elliptical galaxy or bulge for our most reliable Sample A. The solid line is the best linear fit (Table 2). Circles and triangles represent mass measurements from stellar and dust/gas disk kinematics respectively. The squares are the Milky Way ($M_\bullet$ determined from stellar proper motions) and NGC 4258 ($M_\bullet$ based on water maser kinematics), the only two spiral galaxies in the sample. (b) Again for Sample A, BH mass versus the central velocity dispersion of the host elliptical galaxy or bulge, corrected for the effect of varying aperture size as described in §2. Symbols are as in panel (a). (c): Same as panel (a) but for Sample B. Circles are elliptical galaxies, squares are spiral galaxies. The solid line is the same least-squares fit shown in panel (a); the dashed line is the fit to Sample B. All BH mass estimates in this sample are based on stellar kinematics. (d): Same as panel (b) but for Sample B. Symbols are as in panel (c).

$$M_{bh} \propto \sigma^{\alpha}$$

$$\alpha \sim 4.8$$

Magorrian et al 1998
Ferrarese & Merritt 2000
Gebhardt et al 2000