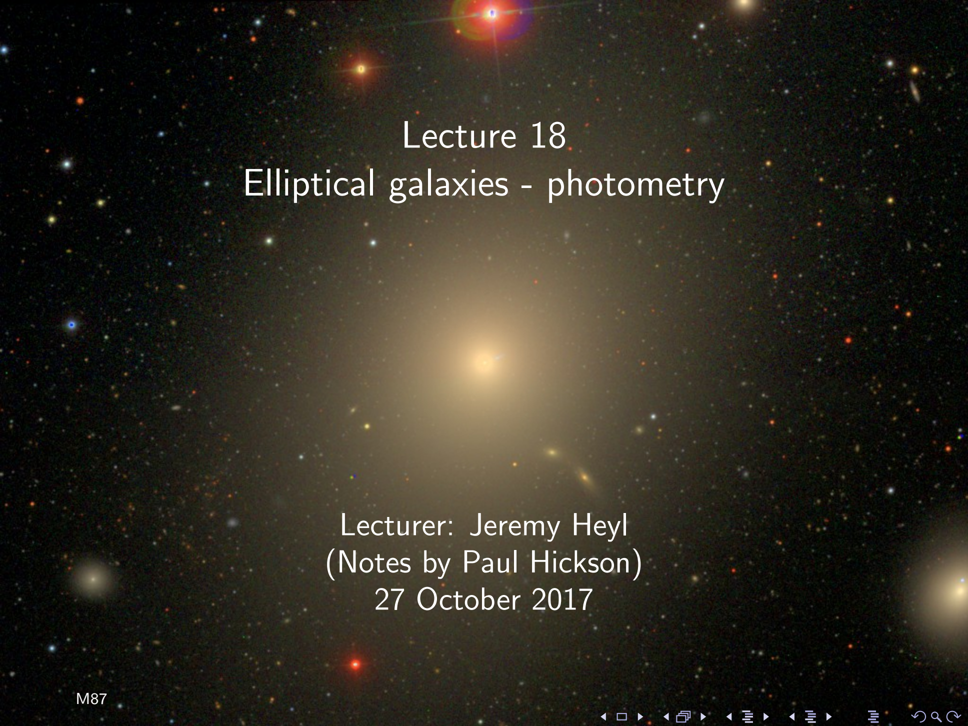
Lecture 18
Elliptical galaxies - photometry

Lecturer: Jeremy Heyl
(Notes by Paul Hickson)
27 October 2017



M87

Photometric properties

Elliptical galaxies have a wide range of sizes and luminosities. It is common to subdivide them:

- Giant elliptical - $L > 2 \times 10^{10} L_\odot \simeq L_*$
- Normal elliptical - $3 \times 10^9 L_\odot < L < 2 \times 10^{10} L_\odot$
- Dwarf elliptical - $L < 3 \times 10^9 L_\odot$

The isophotes of an elliptical galaxy are very close to true ellipses. If a and b are the semi-major and semi-minor axes, respectively, the **ellipticity** is defined by

$$\epsilon = 1 - b/a.$$

(Note that this differs from the *eccentricity*, $e = \sqrt{1 - b^2/a^2}$.)

Elliptical galaxies are assigned a number, En, $n = 0, 1, 2, \cdots, 7$, representing the degree of flattening. $n = 10\epsilon$, rounded to the nearest integer. No elliptical galaxies have been found with $n > 7$.

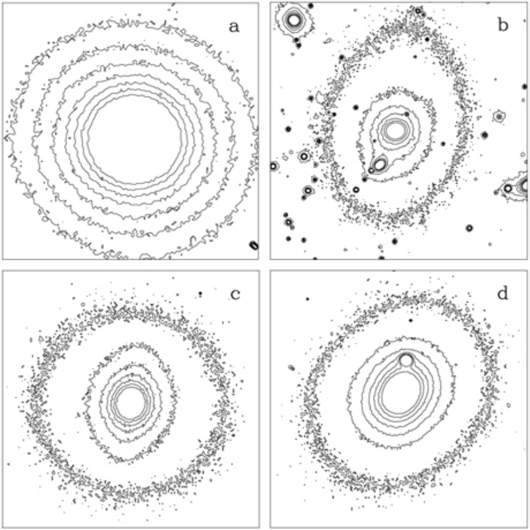


Fig 6.1 (R. de Jong) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Isophotes in the R band of four giant elliptical galaxies: (a) elliptical isophotes (NGC 5846); (b) rotating isophotes (EFAR J16WG); (c) 'disky' isophotes, with $a_4 \simeq 0.03$ (Zw 159-89); (d) 'boxy' isophotes, with $a_4 \simeq -0.01$ (NGC 4478).

Intensity profiles

Intensity profiles normally show the graph of an isophote vs the radius R of a circle that has the same area.

These profiles are generally well-fit by a Sérsic profile

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

where R_e, b and n are constants (not related at all to the number n associated with the ellipticity).

The constant b is defined chosen so that the contour I_e associated with radius R_e, contains half of the total light. For $n > 1, b \simeq 1.999n - 0.327$.

If $n = 1$ this reduces to an exponential profile. The case $n = 4$ corresponds to **de Vaucouluers law**

Intensity profiles

Luminous ellipticals are usually fit well by a de Vaudouleurs ($R^{1/4}$) law. Dwarf ellipticals are often have profiles that are closer to an exponential.

Supergiant ellipticals are found in some clusters. These have the designation **cD** and called cD-galaxies.

cD galaxies have extended luminous envelopes. They are found in the centres of rich clusters of galaxies and have likely accumulated stars pulled off other galaxies in the cluster during tidal interactions.

Some elliptical show faint shell-like structures. These are now understood to result from streams of stars from smaller galaxies that have been captured and pulled apart.

These shells dissipate after a few Gyr, so they are indicative of a fairly recent merger.

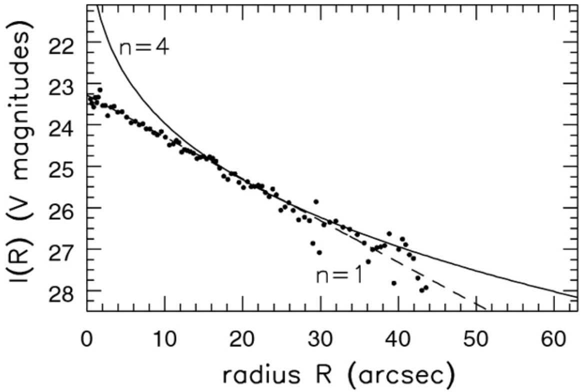


Fig 6.2 (H.Jerjen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Sersic (n = 4: solid) and exponential (n = 1: dashed) profiles. Points show V -band surface brightness for dE galaxy VCC753. This elliptical has $R_e = 15.8$ arcsec in the B band and $I_B(R_e) = 24.4$ mag arcsec^{-2}. Extrapolating the profile outward gives total apparent magnitude $B_{T0} = 16.4$; for $d = 16$ Mpc, we find $L \simeq 1.1 \times 10^8 L_\odot$.

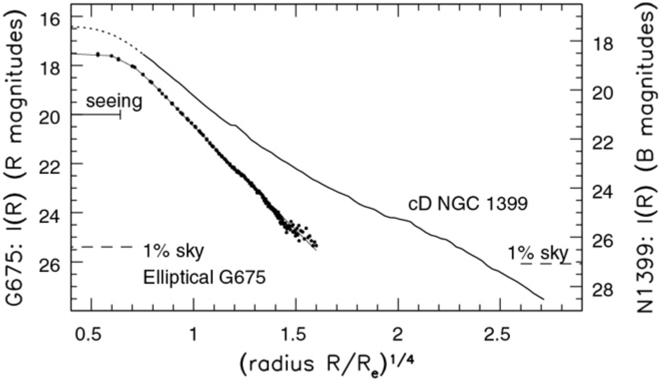


Fig 6.3 (Saglia, Caon) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Surface brightness of two luminous ellipticals: $n = 4$ ($R^{1/4}$ law) corresponds to a straight line. Dots show the R-band surface brightness for galaxy G675. It has $L_V \simeq 2 \times 10^{10} L_\odot$, and $R_e = 4.95$ arcsec (3.8 kpc). The curve gives an $R^{1/4}$ profile, smoothed by atmospheric seeing. The upper curve shows the B-band profile of cD galaxy NGC 1399, which is $\sim$ twice as luminous as G675. For it, $R_e = 15.7$ arcsec (1.4 kpc, so measurements cover $R \lesssim 850$ arcsec (75 kpc). Between the dotted region, where seeing has affected the measurement, and $R \sim 24 R_e$, $I(R)$ follows the $R^{1/4}$ profile closely.

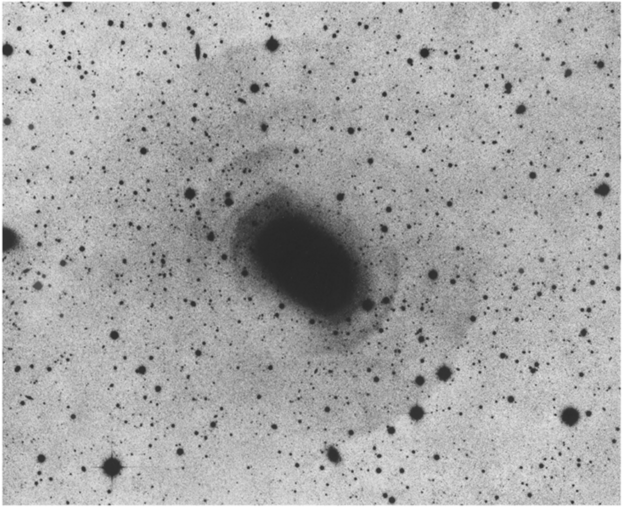


Fig 6.5 (D. Malin) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

This negative image shows faint arclike shells around elliptical galaxy NGC 3923, a luminous galaxy in a loose group. An out-of-focus copy was subtracted from the original photograph, allowing faint but sharp features to stand out. The picture is 18 arcmin (110 kpc) across.

Isophote shapes

Small deviations from elliptical isophotes are often found. The difference between $r(\theta)$ for the isophate and the best-fitting ellipse can be described by a series expansion,

$$\Delta r = \sum_{k \geqslant 3}^{\infty} [a_k \cos(k\theta) + b_k \sin(k\theta)]$$

The $k = 0, 1, 2$ terms are zero by virtue of subtracting the best-fitting ellipse.

The a_3 and b_3 terms describes egg-shaped isophotes, and are normally very small.

The b_4 term is also small since θ is measured from the major axis about which the isophote is symmetric.

If $a_4 > 0$, the isophote is **disky** or slightly diamond-shaped.

If $a_4 < 0$, the isophote is **boxy** or slighly rectangular.

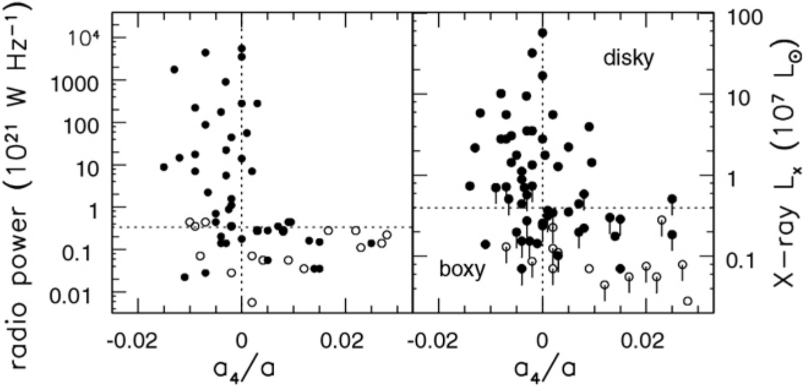


Fig 6.11 (R. Bender) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Radio and X-ray power of elliptical galaxies. Boxy galaxies tend to be strong sources; disky ellipticals are usually weak. Filled circles show bright objects, with $M_B \lesssim 19.5$; open circles are dimmer galaxies. Points with downward-extending bars show upper limits on the X-ray emission.

Global correlations

One finds that the size of an elliptical galaxy correlates with its luminosity and surface brightness. More-luminous galaxies have lower central surface brightness and larger **core radius** r_c (the radius at which the intensity drops to half its central value).

Elliptical are generally confined to a surface in a three dimensional space spanned by luminosity, intensity and radius. This surface is called the **fundamental plane**.

Other systems such as dwarf spheroidal galaxies and globular clusters are found in different, separate, regions of this space.

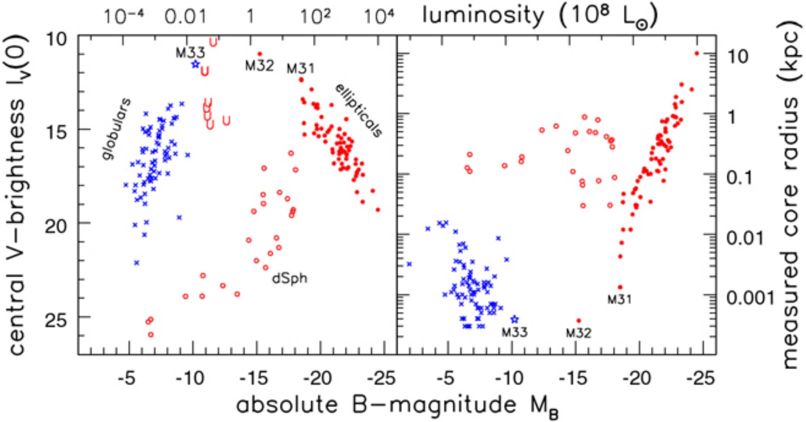


Fig 6.6 (Kormendy, Philipps) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Central surface brightness $\mu_V(0)$, in mag arcsec$^{?2}$ in the V band, and core radius r_c plotted against B-band absolute magnitude M_B . Filled circles represent elliptical galaxies and bulges of spirals (including M31); open circles are dwarf spheroidals; crosses are globular clusters; the star is the nucleus of Sc galaxy M33. 'U' denotes an ultracompact dwarf elliptical.

Cusps and cores

In the centres of elliptical galaxies, two distinct types of intensity profiles are found

- cores - the intensity approaches a constant value as $R \to 0$.
- cusps - the intensity continues to rise as $R \to 0$.

Galaxies with cores tend to be slow rotators and have boxy isophotes.

Galaxies with cusps tend to be faster rotators and have disky isophotes.

The reason for this dichotomy is not clear, but may have something to do with whether these galaxies formed by mergers of gas-rich galaxies (**wet mergers**) or gas-poor galaxies (**dry mergers**).

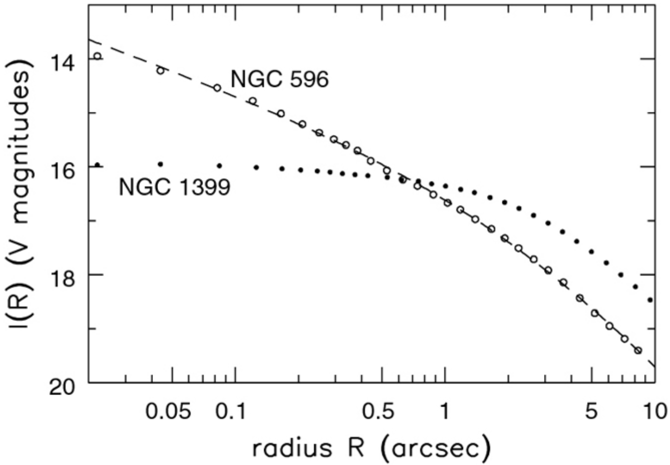


Fig 6.7 (T. Lauer) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Surface brightness $\mu_V(R)$ in the V band at the centres of two elliptical galaxies. The cD galaxy NGC 1399 ($M_V = -21.7$) has a core at $R \lesssim 1$ arcsec, where $\mu(R)$ is nearly constant. In NGC 596 ($M_V = -20.9$) the surface brightness continues to rise as a cusp. The dashed line shows $I(R) \propto R^{-0.55}$.

Intrinsic shapes

The elliptical isophotes that we observe are a two-dimensional projection of the intrinsic shape of the galaxy, which depends on the orientation of the galaxy.

Oblate, or **prolate**, spheriods have a density distribution described by

$$\rho(\boldsymbol{x}) = \rho(m^2), \quad \text{where } m^2 = \frac{x^2 + y^2}{A^2} + \frac{z^2}{B^2},$$

where A and B are constants. If $B < A$ the spheroid is oblate and if $B > A$ it is prolate.

Triaxial ellipsoids have the the equation

$$m^2 = \frac{x^2}{A^2} + \frac{y^2}{B^2} + \frac{z^2}{C^2}$$

Intrinsic shapes

For any particular galaxy we do not know the orientation and so cannot determine the true shape. However, we can learn about the true shape by statistical analysis.

For oblate or prolate shapes, the observed axis ratio $q = b/a$ is related to the intrinsic axis ratio B/A by the equations

$$q^2 = \begin{cases} (B/A)^2 \sin^2 i + \cos^2 i & B < A \text{ (oblate)} \\ [(B/A)^2 \sin^2 i + \cos^2 i]^{-1} & B > A \text{ (prolate)} \end{cases}$$

where the inclination angle i is measured from the axis of rotational symmetry (z axis) to the line of sight.

If we look at a large sample of elliptical galaxies, and assume that they have random inclinations and a given intrinsic axis ratio B/A, we can predict the distribution of q and compare it to observations.

Intrinsic shapes

For randomly-oriented galaxies, the probability of the inclination i falling in the range $(i, i + di)$ is equal to the area on the hemisphere $i < \pi/2$ of the annulus between i and $i + di$, divided by the area of the entire hemisphere. Thus,

$$f_i(i)di = \frac{2\pi \sin i \, di}{2\pi} = \sin i \, di, \quad i < \pi/2.$$

so $f_i(i) = \sin i$.

The probability of the apparent axis ratio q falling in the range $(q, q + dq)$ is $f_q(q)dq$. These probabilities are related by

$$|f_q(q)dq| = |f_i(i)di|,$$

Therefore,

$$f_q(q) = \frac{f_i(i)}{|dq/di|} = \frac{\sin i}{|dq/di|}.$$

Intrinsic shapes

Evaluating the derivative, one finds

$$f_q(q) = \begin{cases} \frac{q}{\sqrt{1-(B/A)^2}\sqrt{q^2-(B/A)^2}} & \text{oblate} \\ \frac{(B/A)^2}{q^2\sqrt{1-(B/A)^2}\sqrt{q^2-(B/A)^2}} & \text{prolate} \end{cases}$$

For flattened disks (oblate spheroids), $f_q(q)$ is almost uniform for $q > B/A$. In fact one observes that the distribution of q for spirals is roughly constant for $q \gtrsim 0.2$ and very few disk galaxies have $q \lesssim 0.1$. So, few disks can be as flattened as $B/A \simeq 0.1$.

Small elliptical galaxies tend to be more elongated (smaller q) than bright ellipticals.

Luminous elliptical galaxies are inconsistent with either of these distributions (oblate or prolate) as there are too few circular galaxies. They are probably triaxial.

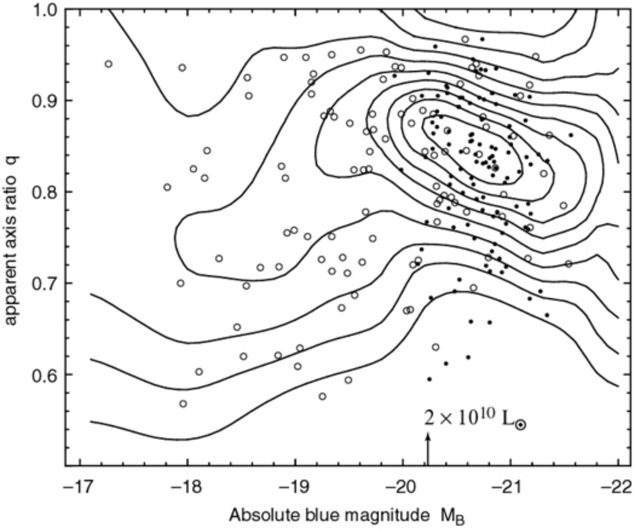


Fig 6.9 (Tremblay & Merritt) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Observed axis ratio q and blue absolute magnitude M_B for elliptical galaxies from two different samples. Bright galaxies (right) on average appear rounder. Contours show probability density.