# Lecture 19
# Elliptical galaxies - kinematics

Lecturer: Jeremy Heyl
(Notes by Paul Hickson)
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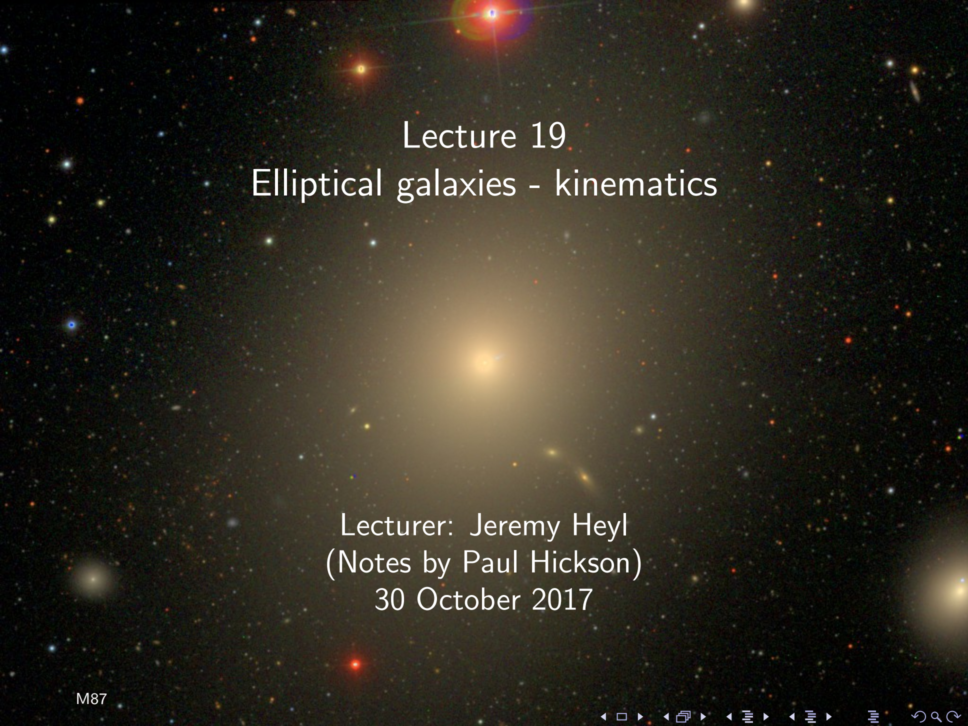

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# Spectroscopy

Radial velocities of stars are measured using a spectrograph (or spectrometer). This instrument takes the light passing through a slit and disperses it in wavelength so that $F_\lambda(\lambda)$ can be measured.

Diffraction, slit width and optical aberrations limit the **spectral resolution** $\Delta\lambda$, the observed width of a narrow emission line.

The **spectral resolving power** is defined by $R = \lambda/\Delta\lambda$. Typically it ranges from a few thousand for a low-resolution spectrograph to several hundred thousand for a high-resolution spectrograph.

For a single star, the observed wavelength $\lambda$ of a spectral line is related to the emitted wavelength $\lambda_0$ by

$$\lambda_0 \simeq \lambda[1 - v_r/c]$$

where $v_r$ is the radial velocity of the star.

# Velocity dispersion

For a galaxy, we must integrate along the line of sight to find the total emission at any position on the sky.

In an elliptical galaxy, stars have random velocities. Taking the $z$ direction along the line of sight, the number density of stars having velocity $v_z$ along the line of site is given by the distribution function $f(\boldsymbol{x}, v_z)$. So the flux that we measure can be written as,

$$F_\lambda(\lambda) = \iint_{-\infty}^{\infty} F_\lambda(\lambda[1 - v_z/c]) f(\boldsymbol{x}, v_z) dz dv_z.$$

Typically, one assumes a Gaussian velocity distribution,

$$\int_{-\infty}^{\infty} dz f(\boldsymbol{x}, v_z) = \exp[-(v_z - V_r)^2/2\sigma_z^2]$$

where $\sigma_z$ (or just $\sigma$) is the velocity dispersion. So,

$$F_\lambda(\lambda) = \int_{-\infty}^{\infty} F_\lambda(\lambda[1 - v_z/c]) \exp[-(v_z - V_r)^2/2\sigma_z^2] dv_z.$$

# Velocity dispersion

This integral is a kind of *convolution*. Each spectral line is broadened due to the velocity distribution of the stars. The greater the velocity dispersion, the broader are the lines.

By measuring the width of the spectral lines, one can infer the velocity dispersion.

The observed central wavelength of the line tells us the systematic velocity, which may be a combination of the Hubble expansion velocity and any rotation of the galaxy.

The velocity dispersion tells us about the random component of the stellar velocities. In the disk of a spiral galaxy, this is small compared to the rotation speed, but in an elliptical galaxy random velocities dominate.

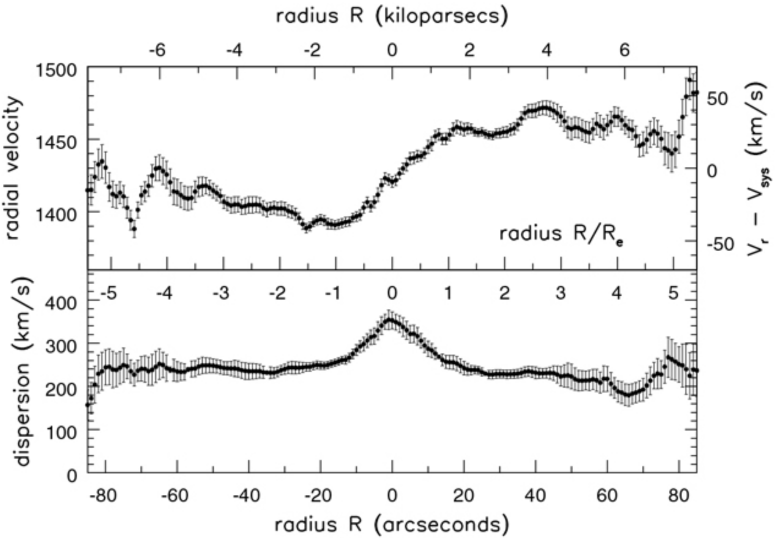

Fig 6.12 (A. Graham) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Measured radial velocity $V_r$ and velocity dispersion $\sigma_r$ on the major axis of cD galaxy NGC 1399; vertical bars show uncertainties. Notice that $(V_r - V_{\rm sys})/\sigma_r \ll 1$; $V_r$ reverses slope in the central few arcseconds.

# The Faber-Jackson relation

in 1976 Sandra Faber and Robert Jackson discovered that the velocity dispersions of elliptical galaxies correlate with luminosity, $L \propto \sigma^4$. In the V band one has

$$\frac{L_V}{2 \times 10^{10} L_\odot} \simeq \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^4 .$$

This is the **Faber-Jackson** relation. It is the equivalent of the Tully-Fisher relation found for spiral galaxies.

Because, for ellipticals, there is a tight correlation between galaxy luminosity, radius and surface brightness, there are different forms that the relation can take, such as

$$R_e \propto \sigma^{1.2} I_e^{-0.8}.$$

This is another example of the *fundamental plane* for elliptical galaxies, in this case in a space spanned by $\sigma$, $R_e$, and $I_e$.

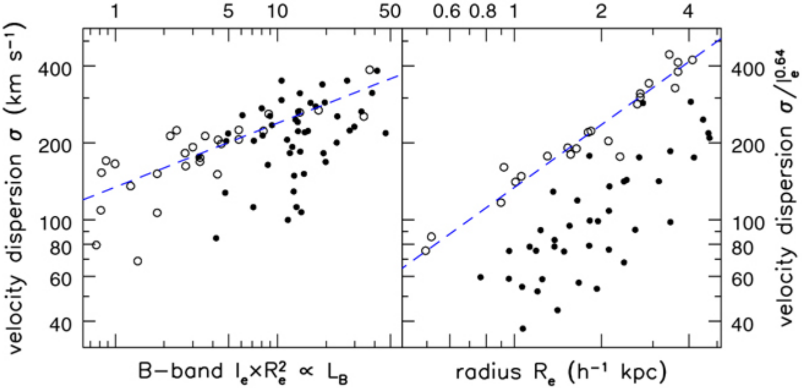


Fig 6.13 (T. Treu) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Left, central velocity dispersion $\sigma$ plotted against $I(R_e)R_e^2$ (proportional to blue luminosity $L_B$). The dashed line shows $L_B \propto \sigma^4$. Right, the fundamental plane. Open circles represent elliptical galaxies in the Coma cluster; filled circles show those at redshifts $0.8 < z < 1.2$.

# Rotation in elliptical galaxies

Rotation can produce oblate shapes, but not prolate or triaxial shapes.

If elliptical galaxies are oblate due to rotation, then the intrinsic axis ratio should be related to the rotation speed. In particular, they should fall close to the dashed line shown in the figure on the next slide.

However, many galaxies have rotation speeds that are much lower than this prediction. So their flattened or elongated shapes cannot be due to rotation.

Instead, elliptical galaxies maintain their shapes because of an **anisotropic velocity distribution**.

The luminosity and isophotal shape is found to correlate with the rotation speed. Luminous ellipticals rotate more slowly and are more likely to have boxy isophotes.

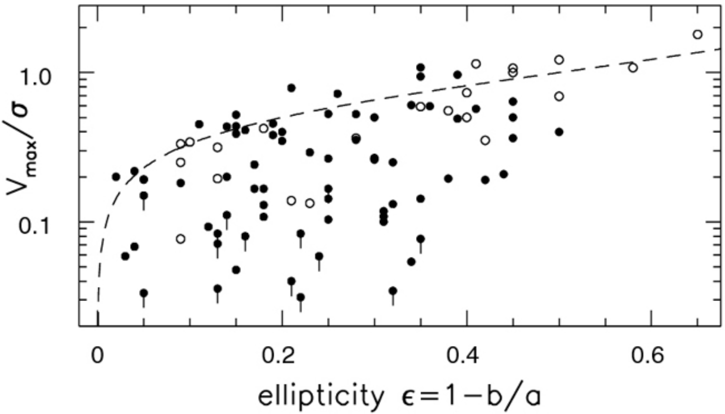


Fig 6.14 (R. Bender) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The ratio of measured peak rotation speed $V_{\text{max}}$ to central velocity dispersion $\sigma$ for elliptical galaxies, plotted against apparent ellipticity. Filled circles show bright galaxies ($M_B < -19.5$); open circles are dimmer galaxies. Points with downward-extending bars indicate upper limits on $V_{\text{max}}$. The dashed line gives $(V/\sigma)_{\text{iso}}$, the fastest rotation expected for a given flattening.

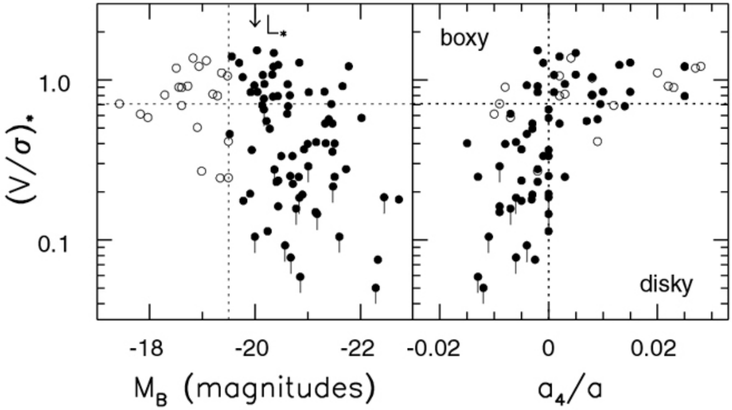


Fig 6.15 (R. Bender) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The ratio $(V/\sigma)_*$ of measured $V_{\mathrm{max}}/\sigma$ to $(V/\sigma)_{\mathrm{iso}}$, the rotation expected for an oblate galaxy according to Equation 6.29. Downward-pointing bars show upper limits on $V_{\mathrm{max}}$; filled circles are bright galaxies, with $M_B < -19.5$ for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. Left, luminous galaxies often rotate slowly, falling below the dotted horizontal line at $(V/\sigma)_* = 0.7$. Right, boxy galaxies, with $a_4 < 0$, are almost all slow rotators; many of these are luminous.

# Violent relaxation

We saw that the relaxation time due to stellar encounters in galaxies is much longer than the age of the Universe. So why are elliptical galaxies so smooth?

The answer was provided in 1967 by Cambridge astrophysicist Donald Lynden-Bell. Lynden-Bell pointed out that when galaxies are being assembled, by mergers of smaller galaxies or proto-galaxies, the gravitational potential can fluctuate wildly on relatively short time-scales.

If the potential is changing, the orbital energies of stars is not conserved. Energy is transferred between stars by forces arising from the fluctuating potential.

The result of this is similar to stellar encounters but much more effective. The motions of the stars are quickly randomized, removing most of any pre-existing structure. This is called **violent relaxation**.

# Stellar orbits in elliptical galaxies

Some insight into orbits in elliptical galaxies can be gained by considering a very simple potential - one that corresponds to the interior of a homogeneous triaxial ellipsoid (ie. constant density). This is

$$\Phi = \Phi_0 + \frac{1}{2}(\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2)$$

where $\Phi_0$ is a constant and $\omega_x$, $\omega_y$ and $\omega_z$ are frequencies that depend on the semi-major axes and the density.

This equation describes a *triaxial harmonic oscillator*. The orbit consists of independent harmonic motion in the $x$, $y$, and $z$ directions with corresponding frequencies.

If the frequencies are not rational multiples of each other, the orbit will completely fill a rectangular box centred on the galaxy and aligned with the principal axes. This is an example of a **box orbit**.

# Stellar orbits in elliptical galaxies

If the potential is axisymmetric (oblate or prolate), orbits take the form of a rosette, with oscillatory motion in a plane that rotates around the axis of symmetry. These are called **loop orbits** (also called *tube orbits*).

Loop orbits do not pass through the centre of the galaxy. They are prevented from doing so by conservation of angular momentum about the symmetry axis.

In triaxial potentials, both box orbits and loop orbits exist. The loops can circle about any of the principal axes.

Loop orbits around the largest or smallest axis are generally stable, but orbits around the intermediate axis are unstable.

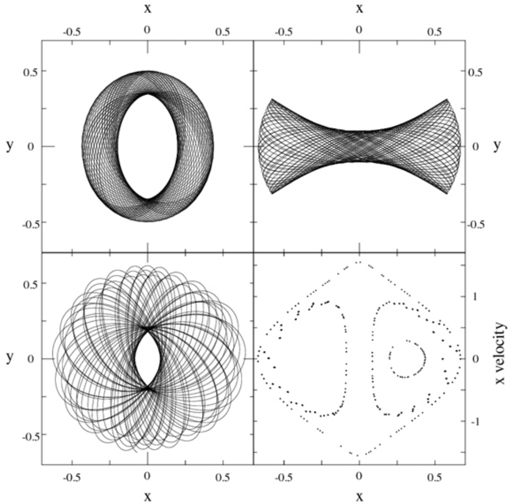

Fig 6.16 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Orbits in a triaxial potential. The top left panel shows a loop orbit, which avoids the center; at the top right is a box orbit, which passes through it; lower left is a chaotic orbit, produced when a central spherical potential is added. The lower right panel shows a surface of section: values of $(x, v_x)$ for all three orbits are plotted each time the orbit crosses $y = 0$ in the direction $v_y > 0$.