## Galactic Interactions & Elliptical galaxies

Cluster transformation Structure & Dynamics Formation of Elliptical Galaxies

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As galaxies move through the ICM, their gas components experience a ram pressure. If this ram pressure is sufficiently strong, it can strip the gas from the galaxy.

Ram-pressure stripping will occur when

$$ho_{
m ICM} > rac{2\pi G \Sigma_* \Sigma_{
m ISM}}{V^2}$$

The potential for new star formation is greatly reduced once gas is removed due to ram-pressure stripping.

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## Strangulation

If a galaxy only had the gas in the ISM available for star formation, it would run through its gas in only a few Gyr. For star formation to last as long as observations indicate, galaxies are thought to be surrounded by reservoirs of gas comprised of

- Gas falling onto the system for the first time
- Gas that has been shock-heated and is cooling
- Gas that has been expelled from the ISM by feedback processes

Both ram pressure and tides can easily strip this gas reservoir from a galaxy, resulting in strangulation. Strangulation therefore results in a slow decline of star formation as the galaxy slowly runs out of fuel.

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## Three classes of elliptical galaxies

In general, elliptical galaxies are smooth, roundish stellar systems that are gas- and dust-poor.

- Bright ( $M_B \leq -20.5$ ) have little rotation, boxy isophotes, and relatively shallow central surface brightness profiles.
- Intermediate luminosity ( $-20.5 \leq M_B \leq -18$ ) are supported by rotation, have disky isophotes, and have steep central surface brightness profiles
- Faint ( $M_B \gtrsim -18$ ) (dwarf ellipticals and spheroidals) have no rotation and exponential surface brightness profiles.

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# Elliptical galaxy observables

To study a galaxy's properties, we need to understand how the observables (line-of-sight projections of 3D quantities) are related to the physical quantities.

Let  $\rho(\vec{x})$  be the 3D distribution of stellar mass in a system, and  $\nu(\vec{x})$  be the 3D distribution of light in a system; the two are related by  $\Upsilon(\vec{x})$ , the stellar mass-to-light ratio.

If Y is a constant, then the normalized surface brightness is

$$I(x,y) = \frac{\Sigma(x,y)}{Y} = \frac{1}{Y} \int \rho(\vec{x}) \, dz$$

and the normalized distribution of the velocity along the line of sight is

$$\mathcal{L}(x, y, v_z) = \frac{1}{\Sigma(x, y)} \iiint f(\vec{x}, \vec{v}) \, dv_x \, dv_y \, dz$$

where  $f(\vec{x}, \vec{v})$  is the phase-space distribution function.

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## Isophotal twists

Some ellipticals reveal isophotal twists, with the direction of the major axis of the isophote changing with isophotal level.

Most of these ellipticals have boxy isophotes.

The simplest explanation is that these elliptical galaxies are triaxial, and have their intrinsic axis ratios change with radius.

In projection, these systems will reveal isophote twist.

The presence of isophotal twists in bright, boxy ellipticals is evidence that these systems are triaxial.



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## The nuclei of elliptical galaxies

The central regions of disky elliptical galaxies have steep cusps, while boxy ellipticals have more shallow cores.



## Elliptical galaxy kinematics

An elliptical galaxy's spectrum is a convolution of the template spectrum, which is the luminosity-weighted spectrum of all the various stars along the line of sight, and a broadening function, which is a combination of the instrumental broadening function and the line of sight velocity distribution (LOSVD).

A typical functional form for the LOSVD is a simple Gaussian

$$\mathcal{L}(v) = rac{1}{\sqrt{2\pi\sigma}} e^{-w^2/2} \qquad w = rac{v-V}{\sigma}$$

However, the LOSVD is generally not Gaussian, and it has become standard practice to adopt a Gauss-Hermite series

$$\mathcal{L}(v) = \frac{1}{\sqrt{2\pi\sigma}} e^{-w^2/2} \left[ 1 + \sum_{j=3}^N h_j H_j(w) \right]$$

The series is typically truncated at N = 4, so the LOSVD is described by four parameters:  $V, \sigma, h_3$ , and  $h_4$ .

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## Elliptical galaxy kinematics

Disky ellipticals typically reveal strong rotation along the major axis, consistent with them being "oblate rotators" (oblate in shape, flattening due to rotation).

Boxy ellipticals reveal very little rotation, and occasionally rotate along the minor axis. The latter is clearly a sign that boxy ellipticals are triaxial.



### Orbital families in triaxial potentials



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It is much more difficult to probe the mass distribution of elliptical galaxies at large radii than in disk galaxies, since there is no organized rotation and the surface brightness profile drops off so quickly.

Combined with the shape of the velocity profiles beyond the second moments (via the Gauss-Hermite moments), the shape of the velocity dispersion as a function of radius depends on M/L.

X-ray mapping shows that  $\sim 100 M_{\odot}/L_{\odot}$  at  $\sim 100$  kpc.

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#### Central supermassive black holes

A massive black hole at a galaxy's center will only significantly influence the dynamics within a radius



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#### Kinetic energy tensor

The dynamics of elliptical galaxies are governed by the collisionless Boltzmann equation

 $\frac{df}{dt} = 0$ 

Multiplying by the velocity and integrating over the velocity-space yields the Jeans equations

$$rac{\partial (
ho \langle v_j 
angle)}{\partial t} + rac{\partial (
ho \langle v_i v_j 
angle)}{\partial x_i} + 
ho rac{\partial \Phi}{\partial x_j} = 0$$

Multiplying all terms by  $x_k$  and integrating over all of space yields

$$\frac{\partial}{\partial t} \int \rho x_k \langle v_j \rangle \, d^3 \vec{x} = -\int x_k \frac{\partial (\rho \langle v_i v_j \rangle)}{\partial x_i} \, d^3 \vec{x} - \int \partial \rho x_k \frac{\partial \Phi}{\partial x_j} \, d^3 \vec{x}$$

#### Kinetic energy tensor

We can use integration by parts to rewrite the first integral on the right-hand side as

$$\int x_k rac{\partial (
ho \langle v_i v_j 
angle)}{\partial x_i} \, d^3 ec x = - \int 
ho \langle v_k v_j 
angle \, d^3 ec x \equiv -2 \mathcal{K}_{kj}$$

where  $\mathcal{K}_{kj}$  is the kinetic energy tensor.

We can split the kinetic energy tensor into the contributions from the ordered and random motions:

$$\mathcal{K}_{ij}\equiv\mathcal{T}_{ij}+rac{1}{2}\Pi_{ij}$$

where

$$\mathcal{T}_{ij} \equiv rac{1}{2} \int 
ho \langle v_i 
angle \, d^3 ec x \qquad \Pi_{ij} \equiv \int 
ho \sigma_{ij}^2 \, d^3 ec x$$

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### Potential energy tensor

We can also define the potential energy tensor

$$\mathcal{U}_{ij} \equiv -\int \rho x_i \frac{\partial \Phi}{\partial x_j} d^3 \vec{x}$$

Combining these two energy tensors, and using that both  $\mathcal{K}$  and  $\mathcal{U}$  are symmetric,

$$rac{1}{2}rac{d}{dt}\int
ho[x_k\langle v_j
angle+x_j\langle v_k
angle]\,d^3ec x=2\mathcal{K}_{jk}+\mathcal{U}_{jk}$$

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#### Moment of inertia tensor

We define the moment of inertia tensor

$$\mathcal{I}_{ij} \equiv \int \rho x_i x_j \, d^3 \vec{x}$$

Differentiating with respect to time, and using the equation of continuity,

$$\begin{aligned} \frac{d\mathcal{I}_{jk}}{dt} &= \int \frac{d\rho}{dt} x_j x_k \, d^3 \vec{x} \\ &= -\int \frac{\partial(\rho \langle v_i \rangle)}{\partial x_i} x_j x_k \, d^3 \vec{x} \\ &= \int \rho[x_j \langle v_k \rangle + x_k \langle v_j \rangle] \, d^3 \vec{x} \end{aligned}$$

Therefore,

$$rac{1}{2}rac{d}{dt}\int
ho[x_j\langle v_k
angle+x_k\langle v_j
angle]\,d^3ec x=rac{1}{2}rac{d^2\mathcal{I}_{jk}}{dt^2}$$

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#### Tensor Virial Theorem

We can then write the tensor virial theorem as

$$rac{1}{2}rac{d^2\mathcal{I}_{jk}}{dt^2}=2\mathcal{K}_{jk}+\mathcal{U}_{jk}$$

which relates the gross kinetic and structural properties of gravitational systems.

If the system is in a steady state, then  $\frac{d^2 \mathcal{I}_{ij}}{dt^2} = 0$  and the tensor virial theorem reduces to

$$2\mathcal{K}_{jk}+\mathcal{U}_{jk}=0$$

The common (scalar) virial theorem 2K + U = 0 is simply the trace of this tensor equation.

## Tensor virial theorem for an axisymmetric system

We can use the tensor virial theorem to relate the flattening of an elliptical galaxy to its kinematics.

Consider an oblate system with its symmetry axis along the *z*-direction. Exploiting this symmetry,

$$\langle v_r 
angle = \langle v_z 
angle = 0 \qquad \langle v_r v_{\phi} 
angle = \langle v_z v_{\phi} 
angle = 0$$

If we write  $\langle v_x \rangle = \langle v_\phi \rangle \sin \phi$  and  $\langle v_y \rangle = \langle v_\phi \rangle \cos \phi$ , then

$$\begin{aligned} \mathcal{T}_{xy} &= \frac{1}{2} \int \rho \langle v_x \rangle \langle v_y \rangle \, d^3 \vec{x} \\ &= \frac{1}{2} \int_0^{2\pi} \sin \phi \cos \phi \, d\phi \int_0^\infty dr \int_{-\infty}^\infty \rho(r,z) \langle v_\phi \rangle^2(r,z) \, dz \\ &= 0 \end{aligned}$$

A similar analysis shows that all other non-diagonal elements of  $\mathcal{T}$ ,  $\Pi$ , and  $\mathcal{U}$  are also 0. In addition, symmetry also gives  $\mathcal{T}_{xx} = \mathcal{T}_{yy}$ , and similar for  $\Pi$  and  $\mathcal{U}$ .

#### Tensor virial theorem

Taking all of these symmetries into account, the only independent, non-trivial virial equations are

$$2\mathcal{T}_{xx} + \Pi_{xx} + \mathcal{U}_{xx} = 0 \qquad 2\mathcal{T}_{zz} + \Pi_{zz} + \mathcal{U}_{zz} = 0$$

If the only streaming motion is rotation about the *z*-axis, then  $T_{zz} = 0$  and

$$2\mathcal{T}_{xx}=rac{1}{2}\int
ho\langle v_{\phi}
angle^{2}d^{3}ec{x}=rac{1}{2}Mv_{0}^{2}$$

where  $v_0$  is the mass-weighted rotation velocity. Similarly,

$$\Pi_{xx} = M\sigma_0^2 \qquad \Pi_{zz} = (1-\delta)M\sigma_0^2$$

where  $\sigma_0^2 \equiv \frac{1}{M} \int \rho \sigma_{xx}^2 d^3 \vec{x}$  is the mass-weighted velocity dispersion along the line of sight, and  $\delta \equiv 1 - \frac{\Pi_{zz}}{\Pi_{xx}} < 1$  is a measure of the anisotropy of the velocity dispersion.

#### Tensor virial theorem

Taking the ratio between the two non-trivial virial equations yields

$$rac{\mathcal{U}_{xx}}{\mathcal{U}_{zz}} = rac{1}{1-\delta} \left(1+rac{1}{2}rac{v_0^2}{\sigma_0^2}
ight)$$

Roberts (1962) showed that this ratio depends only on the ellipticity,  $\varepsilon$ , for systems stratified on similar coaxial oblate spheroids. Therefore, stellar systems can be flattened only by either rotation ( $v_0^2 > 0$ ) or anisotropic velocity dispersion ( $\delta > 0$ ).

It is common to identify  $\sigma_0$  with  $\overline{\sigma}$  (the average velocity interior to  $0.5R_e$ ) and  $v_0$  with  $\frac{4v_m}{\pi}$  (where  $v_m$  is the maximum rotation velocity).

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#### Tensor virial theorem

For the isotropic case ( $\delta = 0$ ),

$$rac{v_m}{\overline{\sigma}} pprox \sqrt{rac{arepsilon}{1-arepsilon}}$$



# Comparison to observations



Emsellem et al. (2011)

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