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Disk instabilities Spiral arm formation Stellar population properties Chemical evolution



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Secular evolution refers to the slow changes in mass and angular momentum that are independent of cosmology.

Main mechanisms for secular evolution include

- Resonance coupling
- ► Gas response
- Bending instability and formation of a bulge

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Resonance coupling

Central bars that develop as a result of the bar mode have a highly flattened, triaxial structure that rotates as a solid body with an angular frequency Ω_p (pattern speed). The potential can then be written as

$$\Phi(r,\phi) = \Phi_0(r) + \Phi_1(r,\phi) \qquad \left|rac{\Phi_1}{\Phi_0}
ight| \ll 1$$

The motion of a star in the unperturbed potential is that of an epicycle with frequency $\kappa(r)$ around a guiding center that rotates around the galaxy center with frequency $\Omega(r)$.

 Φ_1 results in a movement of the star in the bar's frame of reference of $\phi(t) = (\Omega(r) - \Omega_p)t$.

The *m*-fold symmetry of Φ_1 will cause the star to be in roughly the same location in the (r, ϕ) plane with a frequency $\Omega_d \equiv m(\Omega(r) - \Omega_p)$.

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Resonance coupling

Resonances will occur between $\kappa(r)$ and Ω_d at several radii. For m = 2, the important resonances are

- Corotation resonance: $\Omega_d = 0 \rightarrow \Omega(r) = \Omega_p$
- Lindblad resonances: $\Omega_d = \pm \kappa(r)$
 - Inner Lindblad resonance: $\Omega(r) - \frac{1}{2}\kappa(r) = \Omega_p$
 - Outer Lindblad resonance: $\Omega(r) + \frac{1}{2}\kappa(r) = \Omega_p$

These resonances will delineate various regimes of orbital orientations, exchange angular momentum between the bar and the stars, and exchange angular momentum between the bar and the dark matter halo.



Response of the gas





Bending instability & Secular bulge formation





Spiral morphology

The spiral structure must be a perturbation of the underlying disk, since it is present in all of the matter density of the disk.

For a sinusoidal variation, the surface density of a disk with m spiral arms is

$$\Sigma(r,\phi) = \Sigma_0(r) + \Sigma_1(r)\cos(m\phi + f(r))$$

Typically, the shape function describing the spiral form is

$$f(r) = f_0 \ln r + \phi_0$$

This is often expressed in terms of the pitch angle, *i*, where

$$\tan i = m \left| r \frac{\partial f}{\partial r} \right|^{-1}$$

For the logarithmic spiral,

$$i = \tan^{-1}\left(\frac{m}{f_0}\right) = \text{constant}$$

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Formation of spiral arm fragments





Spiral density waves



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Bar-driven spiral arms

Gravity from the rotating non-axisymmetric part of the stellar distribution (the bar) perturbs the disk material.

- Force on orbiting objects larger than average when the ends of the bar make their closest approach; smaller than average between.
- Other things being equal, this alternately speeds up and slows down the orbital speeds.



Global trends in the stellar population of disk galaxies

The stellar birthrate of a galaxy can be approximated as

$$b\equiv rac{\mathrm{SFR}}{\langle\mathrm{SFR}
angle}$$

where the average star formation rate, $\langle SFR \rangle = M_*/t_0$; $t_0 \simeq 10^{10}$ yr is the age of the universe.



Global trends in the stellar population of disk galaxies



Evolution of stellar population trends



Noeske et al. (2007)

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Stellar population gradients NUV-r color gradient (Pan et al., 2014)



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