Galaxies  Astro 530
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Spiral Structure (Part 2)
Spiral structure in galaxies

something interesting that happens in a disk
can reveal physical conditions in that disk
can transfer angular momentum outwards

otherwise doesn't greatly affect formation & evolution of galaxy
there are different types of spiral structure, but spiral structure requires:

**differential rotation (for all)**

**gas (for all but tidal arms)**
Why low mass galaxies have weak spiral structure

**Rotation curves of high & low mass galaxies**

- **High mass disk (spiral galaxy)**
  - Large $V_{\text{max}}$ and flat at large $r$

- **Low mass disk (dwarf galaxy)**
  - small $V_{\text{max}}$ and close to solid body rotation

**Angular speed curves of high & low mass galaxies**

- **High mass disk (spiral galaxy)**
  - Lots of differential rotation ($\Omega$ varies a lot with radius)
  - $\Rightarrow$ strong spiral arms

- **Low mass disk (dwarf galaxy)**
  - little differential rotation ($\Omega$ nearly constant with radius)
  - $\Rightarrow$ weak spiral arms

$\Omega = \frac{V_{\text{rot}}}{r}$ (km/s/kpc)
Gas needed for (most) spiral structure

• In order to have structures in a disk, the stuff making up the structure needs to have sufficiently small random motions. If random motions are too large, the stuff doesn’t stay in the structure.

• Gas can have small random motions. It is *collisional* and can therefore dissipate energy & dynamically cool (reduce motions).

• Stars are *collisionless*. They can be dynamically heated (increase motions) but not cooled.
S0 galaxies: Disk galaxies without gas & therefore no spiral structure
how long does spiral structure last in disk with only stars after gas removed?

D100 in Coma cluster – ongoing ram pressure stripping of gas – no gas or star formation in outer disk stripped ~200 Myr ago -- still strong spiral structure in stellar disk (arm-interarm contrast ~2:1)

D99 in Coma cluster – no gas or dust or ongoing star formation star formation stopped ~500 Myr ago due (probably) to ram pressure stripping; very weak spiral structure in stellar disk remains – but will continue to fade (arm-interarm contrast ~1.05:1)
3 types of spiral structure
physically 3 different things happening although common physical elements

1. Grand design spirals (density waves)
2. Flocculent spirals (stochastic)
3. Tidal material spiral arms

Can have multiple types of spiral structure within 1 galaxy

Critical common elements: differential rotation (for all), gas (for all but tidal arms)
major merger simulation: watch development of spiral features
Tidal arms can drive strong density waves & be connected to density wave arms.
Grand design Spiral arms

Spiral-shaped regions of enhanced density and enhanced star formation

Two effects make grand design Spiral arms

1. “traffic jams” of stars & gas in arms
2. Star formation triggered in arms
Two effects make Grand design Spiral arms

1. “traffic jams” of stars & gas in arms

• Stars in arms now DON’T STAY in arm, they pass through arm
• Arm is region of extra mass & density → extra gravity in arm causes stars to slow down
• A wave caused by disturbance to disk → arms are “density waves”
Traffic jam

"Shockwave traffic jams recreated for the first time"
(Source: Mathematical Society of Traffic Flow, University of Nagoya, Japan)
http://www.youtube.com/watch?v=Suugn-p5C1M
Density wave as rotating pattern

\[ V_{\text{rot}} (\text{km/s}) \]

Ω = \( V_{\text{rot}} / r \) (km/s/kpc)

Density wave pattern
Stars & gas

\( r_{\text{CR}} \)

r (kpc)

Density wave pattern
Solid body rotation

Stars & gas – differential rotation

\( \Omega = V_{\text{rot}} / r \)


NOTE -- in reality:
• Pattern exists over limited range in radius
• Pattern speed may vary with radius or time
• Can have more than one pattern in galaxy

\( r_{\text{CR}} = \text{“corotation radius” orbital speed of stars & gas match pattern speed} \)

stars & gas orbit \textbf{faster} than pattern
(road crew analogy)

stars & gas orbit \textit{slower} than pattern
(traffic cop analogy)
• I’ll come back to discuss SDWs – but first I want to discuss the other effect...
Two effects make Grand design Spiral arms

2. **Star formation triggered in arms**

Gas cloud compressed when it enters density wave, triggering star formation.

The most massive young stars are blue and very luminous, AND they explode as Supernovae shortly after they form, before they get far from spiral arm.

So luminous massive stars seen near arm, not between arms.
Density wave spiral arms

blue stars downstream from dust in spiral arms of grand design spiral galaxy M51
spiral density wave in gas with star formation
Star formation in density wave spiral arms

OB stars explode as supernovae within a few $10^6$ yr after formation, leading to excess of young blue massive stars near spiral arm.
star formation offset from old stellar spiral arm

“arm” of young stars

arm of old stars (density wave)

NGC 2903
How spiral structure affects star formation

- Spiral arms have very little influence on large-scale star formation rates, but they do organize the pattern of star formation in a galaxy.

- Doesn’t affect rates in gas-rich inner disks probably since molecular gas there is already forming stars as fast as it can.

- Might have bigger effect on SF in HI-dominated outer galaxy, since arms could make more dense molecular gas than would otherwise form (Elmegreen 2011).

Elmegreen & Elmegreen 1986
arms don’t affect global SFRs much...
... what do they do?

*they can redistribute angular momentum*...

I will talk about this when we discuss BARS
• back to SDWs
Arm-interarm contrast in near-infrared (~old stars) in M51 is ~2:1-3:1 (large effect!)

Spitzer 3.6\(\mu\)m image of M51

Rix & Rieke 1993

Lots of extra mass & gravitational force in arms
Kinematics of spiral density waves

SDWs cause perturbations to Velocity field

Observed perturbation depends on distance from line-of-nodes

Azimuthal streaming motions observed along l-o-n (major axis)

Radial streaming motions observed perpendicular to l-o-n (minor axis)

Chung et al. 2009
Compare to velocity field in *Flocculent spiral* NGC 4414 – only weak kinematic disturbances in arms

While some weak stellar arms (density wave?) are seen in NIR image (arm enhancement ~30% above interarm), most of the star formation (Hα) and HI is not associated with these arms & there are only small perturbations to velocity field due to these arms

→ Most of spiral structure is stochastic

Thornley & Mundy 1997
spiral arms induce “streaming” (non-circular) motions
Spiral arm streaming motions in spiral density wave (deviations from circular motion)

- gas density
- radial velocity
- azimuthal velocity

Spiral arms

2 spiral arms

Model

CO data

Radial velocity

Gas density

Azimuthal velocity

Gas density

Shetty+2007

Must average over spiral arm streaming motions to get good circular speed curve
How trailing arm perturbs orbit to strengthen itself

Particle is pulled outwards by extra mass of spiral arm. This slows it down in azimuthal (rotational) direction. It starts to fall back (radially) near the peak of the arm. Extra mass of arm keeps the orbit near arm for ‘extra time’, reinforcing arm.

*This works for trailing arm but not leading one, most effective at certain pitch angle. Works for flocculent arms as well as density wave arms; for gas & stars.*
Under what conditions does perturbation to stellar orbit reinforce SDW?

a.) arm is trailing

b.) perturbing frequency < epicyclic frequency

If periodic pull of spiral (perturbing frequency $m |\Omega_p - \Omega| )$ is faster than natural in-out (radial) frequency of star on its orbit (epicyclic frequency $\kappa$), the stars cannot respond fast enough to reinforce spiral, so wave dies out.
What is the orbit of the Sun in the Milky Way?
What is the orbit of the Sun in the Milky Way?

at first ignore star-star collisions i.e., assume a spatially smooth & time-independent gravitational potential

Gravitational potential \( \Phi(x) \) of star cluster or galaxy

The total potential is the sum of a smoothly varying shallow potential well due to the average effect of many distant stars, plus a steep potential well near each star. In some (but not all!) cases the steep potential well near each star can be ignored.
Point mass (Kepler potential)

- $\phi = -\frac{GM}{r}$
- $F = \frac{GMm}{r^2}$ \[NOTE: F \sim r^{-2}\]
- $v_c = \left[\frac{GM}{r}\right]^{1/2}$
- Can have bound or unbound orbit
- Bound orbits are elliptical with period $T_\phi = T_r = 2\pi \left[\frac{a^3}{GM}\right]^{-1/2}$
  equal periods! closed orbit
- $a =$ semi-major axis
- Get this by solving equation of motion
- Bound orbits are ellipses with gravitational center at one focus

$r_1 = r_a =$ apocenter radius
$r_2 = r_p =$ pericenter radius

center of ellipse is not at center of mass
CM is one focus of ellipse
what is the radial distribution of mass most opposite from a point source yet still physically stable?

A. density $\rho(r) \sim r^{-1}$
B. density $\rho(r) \sim r^{-2}$
C. constant density
D. density $\rho(r) \sim r^{1}$
E. density $\rho(r) \sim r^{n}$
what are orbits like inside a Constant Density Sphere?

sphere with radius $r_{sph}$
density $\rho_c$

examine orbits that are completely inside the sphere

the central regions of some galaxies are not too different from constant density
Constant density sphere
(spherical harmonic oscillator potential)

- $\phi(r) = -2\pi G \rho_c (r_{sph}^2 - r^2/3) \quad r < r_{sph}$
- $\phi(r) = -4\pi G \rho_c r_{sph}^3/3r \quad r > r_{sph}$

inside sphere ($r < r_{sph}$), potential has the form:
- $\phi = -1/2 \ W^2 r^2 + \text{constant}$
- $F = m \Omega^2 r \quad \text{[NOTE: } F \sim r \text{]}$
- $v_c = [4\pi G \rho_c/3]^{1/2} r$
- $T_\phi = 2 \ T_r = [3\pi/G \rho_c]^{1/2}$

*radial period is exactly $1/2$ the azimuthal period!*

$\rightarrow$ closed orbit

- Bound orbits are ellipses with gravitational center at ellipse center
**azimuthal period** $T_\phi$

time it takes for one full azimuthal cycle $\phi = 0 \rightarrow 2\pi$

**radial period** $T_r$

time it takes for one full radial cycle $r = r_1 \rightarrow r_2 \rightarrow r_1$

point mass $T_\phi = T_r$

constant density sphere $T_\phi = 2 \ T_r$
mass distributions $\rho(r)$ in Galaxies are in between point sources & constant density spheres

- e.g. “isochrone” potential
- $\phi = -\frac{GM}{(b + [b^2+r^2]^{-1/2})}$
- approaches constant potential as $r\rightarrow0$
- approaches point mass as $r \gg b$

In general:
- $T_\phi = \beta T_r \quad 1 < \beta < 2$
  
  *star completes radial oscillation before moving $2\pi$ in azimuth*

- In most cases $\beta = \frac{2\pi}{\Delta \varphi}$ is irrational then orbit is not closed
- Bound orbits are rosettes
Rosette orbit
For orbit in plane of disk
star oscillates in radius as it orbits

$$\kappa = \text{epicyclic frequency} = \frac{2\pi}{T_r}$$

= frequency of in-&-out (radial) motion

$$\Omega = \text{angular frequency} = \frac{2\pi}{T_\phi}$$

= frequency of angular motion

For Sun in Milky Way:  $$\frac{\kappa_o}{\Omega_o} = 1.3$$
Sun makes 1.3 radial oscillations for every complete orbit around Galactic Center

orbit not closed – orbit is rosette

$$T_\phi = \frac{2\pi}{\Omega_o} = 240 \text{ Myr} \text{ ("galactic year") }$$

$$T_r = \frac{2\pi}{\kappa_o} = 170 \text{ Myr}$$
epicyclic frequency = \( \kappa = \frac{2\pi}{T_r} \)

frequency of in-&-out (radial) motion

\[ \kappa^2(R) = 2 \frac{V}{R} \left( \frac{V}{R} + \frac{dV}{dR} \right) \]

depends on: mass distribution or rotation curve & its gradient

2 extreme cases:

Point mass (Kepler potential)

\[ V(R) \sim R^{-1/2} \]

\[ \kappa = \Omega \]

Constant density sphere

\[ V(R) \sim R \]

\[ \kappa = 2\Omega \]

in general \( \Omega < \kappa < 2\Omega \)
For orbit *perpendicular* to plane of disk
star oscillates vertically as it orbits

\[ \nu = \text{vertical epicyclic frequency} \]
\[ = \text{frequency of up-&-down (vertical) motion} \]

For Sun in Milky Way: \( \nu_o / \Omega_o = 2.7 \)
Sun makes 2.7 vertical oscillations for every complete orbit around Galactic Center

orbit not closed – orbit is rosette

\[ T_z = \frac{2\pi}{\nu_o} = 87 \text{ Myr} \]

\[ \nu_o \approx [4\pi G \rho_o]^{1/2} \] for (nearly) constant density disk
\[ \rho_o = \text{density at disk midplane} \]

*In general* \( \nu_o \) *depends on disk mass density and vertical mass distribution of disk*
Orbit of star in disk of milky way showing vertical motion
How is this orbit wrong?
(for Sun in Milky Way?)
How is this orbit wrong?
(for Sun in Milky Way?)

1. Most orbits not closed
2. Sun makes \(~2.7\) vertical oscillations for every full (azimuthal) orbit, not 4
Under what conditions does perturbation to stellar orbit reinforce SDW?

Perturbation to stellar orbit reinforces SDW if:

a.) arm is trailing

b.) \( m \left| \Omega_p - \Omega \right| < \kappa \)

\( m = \text{number of arms} \)

perturbing frequency < epicyclic frequency

If periodic pull of spiral (perturbing frequency \( m \left| \Omega_p - \Omega \right| \)

is faster than natural in-out frequency \( \kappa \), the stars cannot respond fast enough to reinforce spiral, so wave dies out

There is a spiral arm pitch angle where this reinforcement is a maximum

i.e. gravitational instability has maximum growth rate

and this is the pitch angle that will form
Where in galaxy does perturbation to stellar orbit reinforce SDW?

perturbing frequency < epicyclic frequency

\[ m \left| \Omega_p - \Omega \right| < \kappa \]

inside CR, \( \Omega > \Omega_p \)

\[ m(\Omega - \Omega_p) < \kappa \]

\[ \Omega - \Omega_p < \kappa / m \]

\[ -\Omega_p < \kappa / m - \Omega \]

\[ \Omega_p > \Omega - \kappa / m \]

outside CR, \( \Omega < \Omega_p \)

\[ m(\Omega_p - \Omega) < \kappa \]

\[ \Omega_p - \Omega < \kappa / m \]

\[ \Omega_p < \Omega + \kappa / m \]
Hidden spiral modes in galaxies: evidence of m=2,3,4 spiral modes in galaxies

Sky-enhanced view

Two-fold Symmetric image

Two-fold Symmetric Image with resonance Locations (I4:1, CR, OLR)

Three-fold Symmetric image

Three-fold Symmetric Image with resonance Locations (I3:1, O3:1)

M101

Elmegreen et al. 1992
M51
Hidden spiral modes in galaxies: evidence of $m=2,3,4$ spiral modes in galaxies

Sky-enhanced view

Two-fold Symmetric image

Two-fold Symmetric Image with resonance Locations (I4:1, CR, OLR)

Three-fold Symmetric image

Two-fold Anti-Symmetric image

Three-fold Symmetric Image with resonance Locations (I3:1, O3:1)

Elmegreen et al. 1992
How does disk respond when you kick it?

Studying how waves propagate in disks tells us about physical conditions in disks which are otherwise unobservable.

Seismology: Earthquake waves & earth’s interior

Helioseismology: Sun’s waves & sun’s interior

Modes of ringing bell
Preceding is for stars & stellar orbits... what about gas?

Simple spiral patterns made from oval gas “orbits”

Gas orbits can’t cross (gas is collisional)
Gas doesn’t follow epicycles like stars
But gas can have streamlines (gas version of orbit) which reinforce spiral pattern
True gas streamlines generally not so simple – may also have shocks
Another important condition for the existence of spiral structure: *Is disk dynamically cold enough for structure to form?*
Is disk dynamically cold enough for structure to form?

Toomre stability parameter $Q$: Fight of gravity vs. pressure & centrifugal forces from rotation

$$Q_{\text{star}} \equiv \frac{\sigma_R \kappa}{3.36 G \Sigma}$$

$\sigma_R = \text{radial velocity dispersion}$
$\kappa = \text{epicyclic frequency}$
$\Sigma = \text{mass surface density}$

If $Q \lesssim 1$ gravity wins, structure can form

- Spiral arms
- Dense (star-forming?) gas clouds

$$Q_{\text{gas}} \equiv \frac{c_s \Omega}{\pi G \Sigma}$$

$c_s = \text{sound speed} \sim \sigma = \text{velocity dispersion}$
$\Omega = \text{angular frequency}$
$\Sigma = \text{mass surface density}$
Disk stars can reinforce a spiral wave and help it grow only if random motions are small enough not to take them outside spiral arms

**Structure can form in disk only if Q<1.5**

- If Q<1.5 in gas & stars, can have SDWs and flocculent arms

- If Q<1.5 in gas but Q>1.5 in stars, might get flocculent arms but no SDWs in stars

- If no gas → Q>1.5 in stars after a while, get SO galaxy with no arms