Spiral Arms (sec 5.5.2 in S+G)

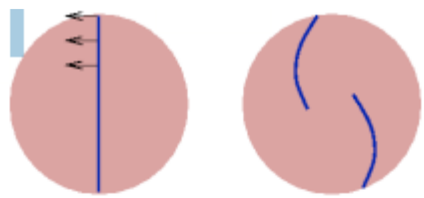
- Defining feature of spiral galaxies - what causes them?
- Observational clues

Seen in disks that contain gas, but not in gas poor S0 galaxy disks.

- Defined by blue light from hot massive stars. Lifetime is << galactic rotation period.

•When the sense of the galactic rotation is known, the spiral arms trail the rotation.

•First ingredient for producing spiral arms is differential rotation.

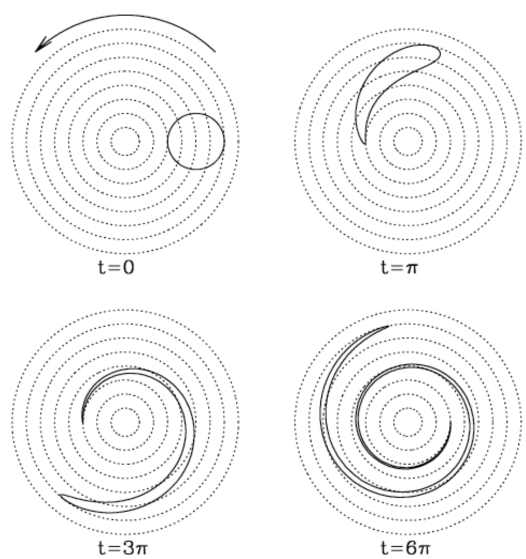


Tips of spiral arms point away from direction of rotation.

(From P. Armitage)

Spiral Arms

- 'Visually' spiral arms are associated with star formation/ molecular gas.
- How to describe: if the arms are 'sinusoidal' $\Sigma(R,\phi)=\Sigma_0(R)+\Sigma_1(R)\cos[m\phi+f(r)]$
  - f(r) shape function of the spiral- if spiral is tightly wound $\partial f/\partial r$ is large
- Differential rotation of disk - for V(r)=constant, $\Omega=V/R$ must vary with R.
  - So a line with a constant azimuthal angle $\phi=\phi_0$ will be sheared into a spiral curve $\phi(R,t)=\phi_0+Vt/R$ at time t.
  - thus a 'blob' will be sheared into a spiral structure



(MBW, fig 11.4)

Spiral Arms (sec 5.5.2 in S+G)

- For galaxy with flat rotation curve:

V(R) = constant

Ω(R) =V/R Angular velocity~1/R

- Any feature in the disk will be wrapped into a trailing spiral pattern due to differential rotation

However this is NOT SOLELY why spiral galaxies have spiral arms- if so they would wrap up into a tight spiral in time scale $\Delta R/R=2\pi R/vt$

putting in values near the sun $\Delta R/R=0.25\ (t/\mathrm{Gyr})^{-1}$

e.g. *The Winding Problem*

If arms were "fixed" w.r.t. the disk

With flat rotation (V ~ const), **inner parts rotate many times compared to outer parts**

E.g. for one rotation at R, two rotations at R/2, four at R/4, 8 at R/8.

This leads to very tightly wound arms.

- Angular frequency $\omega=V_c/R$- spirals have flat rotation curve V_c= constant

$d\omega/dr=v/r^2$ angle $\phi=\omega t$, $d\phi=t d\omega=v/r^2\ t dr$

so $\tan\psi=dr/r\ d\phi=r/vt=1/\phi$

pitch angle, ψ , steadily decreases as the pattern rotates- after 1 rotation

$\tan\psi=1/2\pi$ ($\psi=9^\circ$) e.g winds up!

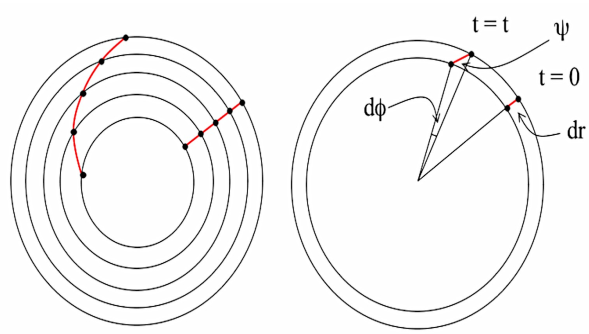
- 2 rotations 4.5° etc

In Sa's ψ ~5° while in Scs ψ~10-30°

SO since galaxies have been around for >> 2 orbital times

- Long lived spiral arms are **not** material features in the disk... they are a pattern, through which stars and gas move
- Short lived spiral arms can arise from temporary patches pulled out by differential rotation

Winding?



Flat rotation curve: v = const; $\Omega = v/r$; $d\Omega = v/r^2\ dr$

Now, $\phi = \Omega \times t$, so $d\phi = d\Omega \times t = v/r^2\ dr\ t$

So $\tan\psi = dr / r\ d\phi = dr / [(v/r)\ dr\ t] = r / vt = 1/\Omega t = 1/\phi$

$\boxed{\tan\psi = r / vt = 1/\phi}$

M. Whittle's web site

Winding

- Thought experiment: paint a stripe on a galactic disk along $\varphi=\varphi_0$
- Disk is in differential rotation with an angular speed $\Omega(R)$
- So the equation of the strip as a function of time is

$$\varphi(R,t)=\varphi_0+\Omega(R)t$$

For a typical spiral galaxy with a flat rotation curve

$\Omega(R) = v_{circularr}/R$; so

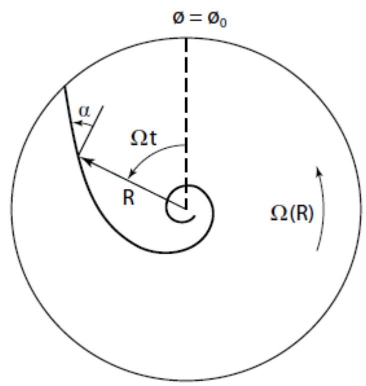
$d\Omega(R)/dR = v_{circular}/R^2$

near the sun $v_{circular}$ =220km/sec at R~10kpc, for t=10^{10}yrs
α=0.25deg !

Real galaxies have α ~5-25 deg

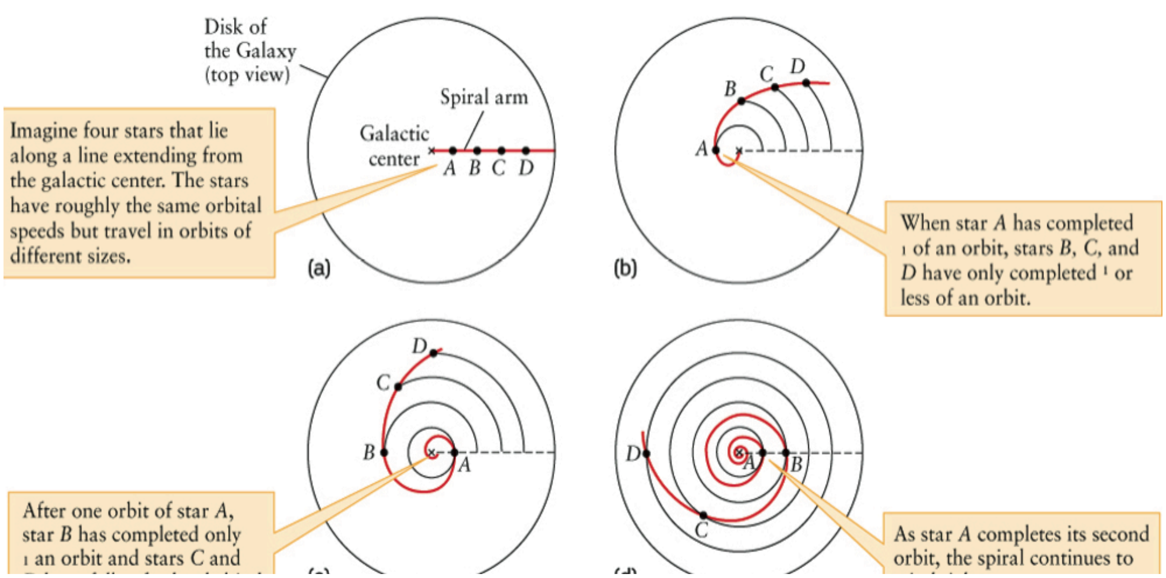
In the diagram

cot (α)~Rt dΩ(R)/dr



From

http://www.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect24/lecture24.html



The formation mechanism of galactic spiral arms in disk galaxies

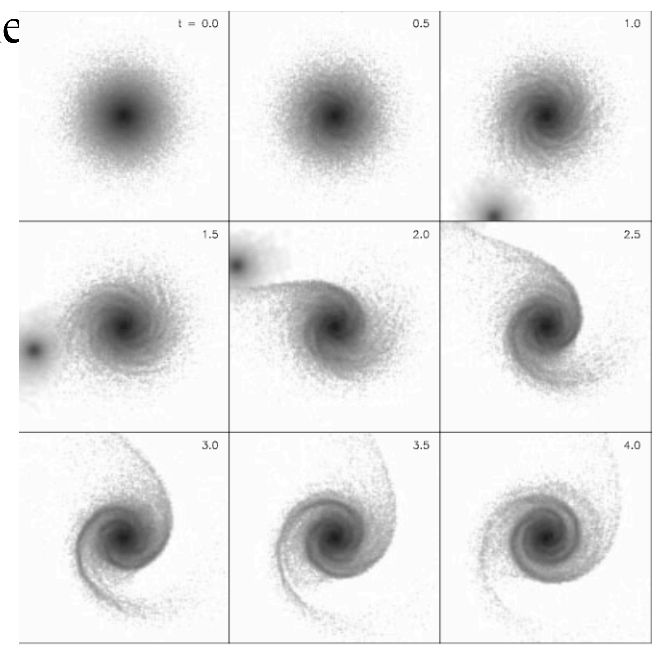
There are apparently several mechanisms via which spiral arms are 'excited'
 tidal interactions with nearby companion galaxies
 by the central stellar bar

However, the spiral arms can also be excited and maintained without external perturbations.

In N-body simulations of multi-arm spiral galaxies, spiral arms are transient and recurrent (e.g., Sellwood & Carlberg 1984; Sellwood 2000; Baba et al. 2009; Fujii et al. 2011).

Another Possible Origin

- Tides between galaxies provoke a two-sided response, like the ocean's response to the tidal pull of the Moon.
- Since the classic two-armed 'grand-design' spiral galaxies M51 and M81 are clearly interacting with close companions, it's very likely that these galaxies owe their symmetric spirals to tidal interactions (J. Barnes)



Tidal encounter between disk and a companion of 1/10th the mass- times in rotation units at 3 scale lengths

Spiral Arm Formation

The fundamental cause of spiral arm formation is not well understood.

- To quote from https://www.cfa.harvard.edu/~edonghia/Site/Spiral_Arms.html

  'The precise nature of spiral structure in galaxies remains uncertain. Recent studies suggest that spirals may result from interactions between disks and satellite galaxies...., here we consider the possibility that the multi-armed spiral features originate from density inhomogeneities orbiting within disks.'
- In this movie spiral arms are formed due to a merger (http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517)

The *Eris* N-body simulation of a massive late-type spiral galaxy in a WMAP3 cosmology (Guedes, Callegari, Madau, & Mayer 2011. The simulation was performed with the GASOLINE code on NASA's *Pleiades* supercomputer and used 1.5 million cpu hours.

M_{vir}=7.9 x 10^{11} M_{sun}
$N_{DM}+N_{gas}+N_{star}$=7M+3M+8.6M within the final R_{vir}
force resolution=120 pc

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Spirals and Dark Matter

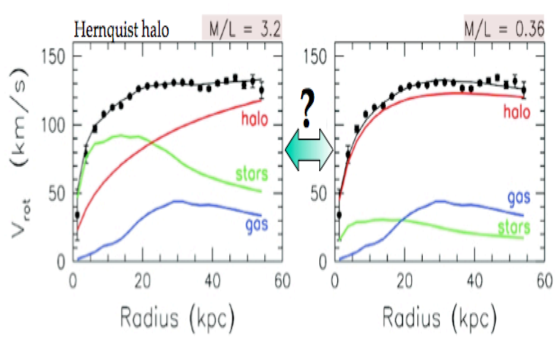
- Rotation-curve decomposition - primary tool for measuring the distribution of dark matter in spiral galaxy halos, **but** uncertainties in the mass-to-light ratio of the luminous disk and bulge make accurate estimates difficult (IMF-mass degeneracy)
- Disk-halo conspiracy- there is no 'feature' in the rotation curve indicating where dark matter starts to dominate- smooth transition!

- Solution is to observe face-on galaxies - position by position, measure both rotation and dispersion components of the velocity
- Disks in equilibrium

  Rotation provides total mass within a given radius.

  Vertical oscillations of disk stars provides disk mass within given height inside a cylinder:

Bershady et al



Solution is that disks have less mass than the maximum allowed by IMF, colors-
At the radius where the velocity curve flattens ~15-30% of the mass is in baryons
Build your own rotation curve (!)
http://burro.astr.cwru.edu/JavaLab/RotcurveWeb/main.html

End of Spirals

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