Einführung in die Astronomie II

Teil 13

Peter Hauschildt
yeti@hs.uni-hamburg.de

Hamburger Sternwarte
Gojenbergsweg 112
21029 Hamburg

13. August 2019

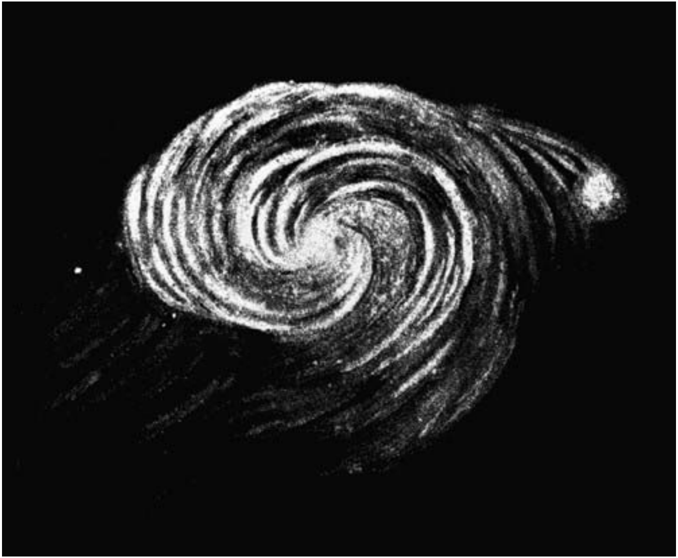
Overview part 13

- historic stuff
- extragalactic distance determination
- classification of galaxies
- general properties
- spiral structure

Historical stuff

- 19th Century observations: Rosse with 60 inch reflector (!)
- discovered "spiral nebulae" (e.g., M51)
- Kant: "island universes"
- astronomers divided about local versus non-local nature of the spiral nebulae
- 1920's debate between Shapley (local) and Curtis (non-local) did not decide the issue
- needed to measure distances to settle the question

Rosse's sketch of M51



Distance determinations !!

- Hubble (1923): discovered Cepheids in the Andromeda (spiral) nebula, aka M31
- P-L relation gives distance!
- modern result: distance of 900 kpc to Sun!
- much farther than size of our Galaxy!
- must be non-local!
- angular size of Andromeda galaxy $\rightarrow$ diameter of 70 kpc
- larger than the Milky Way!

primary distance indicators !!

- cepheids
- brightest giants and super-giants
- novae

secondary distance indicators

- diameter of largest H II region
- brightest blue stars
- brightest globular clusters
- planetary nebulae
- Supernovae

tertiary distance indicators

- luminosity classes of galaxies
- width of emission lines
- brightest galaxy in clusters
- M-L relation (galaxies)
- color-L relation (galaxies)

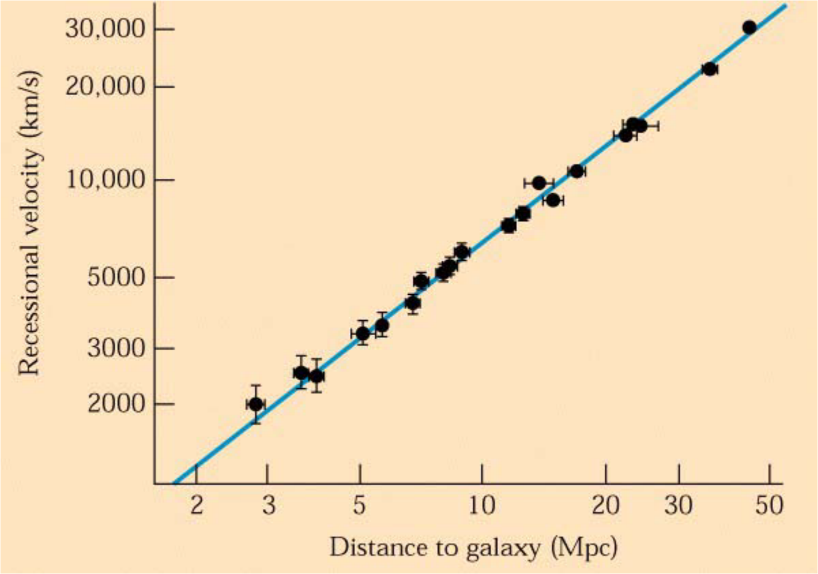
The Hubble Law !!

- Slipher (1911): spectral lines in spiral nebulae are mostly redshifted
- Hubble & Humason (1920's): correlation between distance and redshift
- the farther a galaxy is away, the larger the redshift (and thus its radial velocity)
- *Redshift of a receding galaxy*

$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

- use Doppler formula to convert z to v

Hubble diagram !!



The Hubble Law !!

- Hubble (1929): relation between distance d and recession speed v

$$v = H_0 d$$

  $\rightarrow$ *Hubble law*
- $H_0 \approx 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$: *Hubble constant*

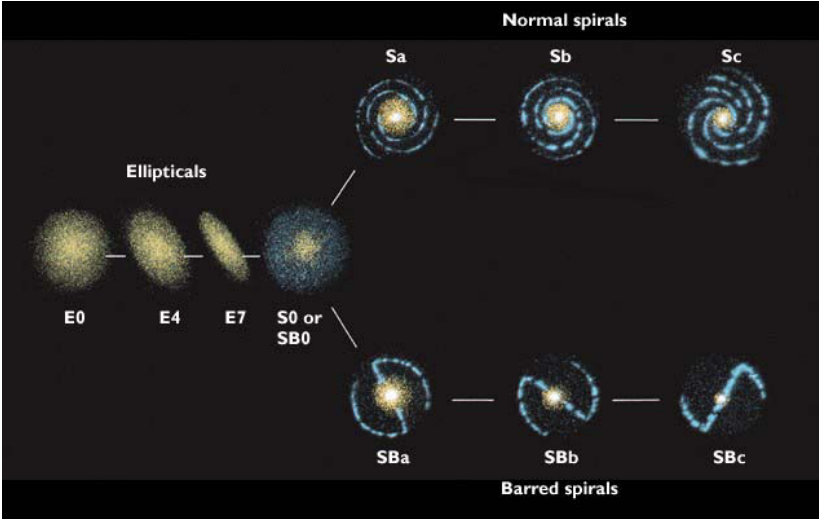
The Hubble Law !!

- example: galaxy at 100 Mpc distance moves away from us at a speed of $6500\,\mathrm{km\,s^{-1}}$
- note: only holds as an average, galaxies have individual velocities, too
- example: M31 is approaching the Milky Way
- H_0 relatively hard to measure accurately: z (and thus v) easy to measure but d is hard to measure accurately.
- Hubble law used to estimate distances to remote objects where no other information is available!

Classification of galaxies

- we can see millions of galaxies in the sky
- Hubble defined 4 broad classes of galaxies
  - spirals
  - barred spirals
  - ellipticals
  - irregulars
- these types have different appearance and different physical characteristics

The Hubble sequence !!



Classification of galaxies

- spiral galaxies are divided into
  - normal (SA) spirals (Sa–Sc, or SAa–SAc)
  - barred (SB) spirals (SBa–SBc)
  - intermediate types (SBA)

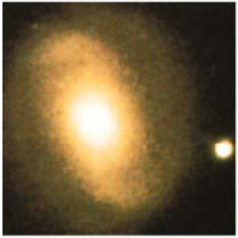
spirals

Sa

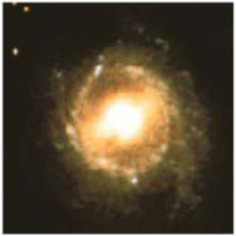
Sb

Sc

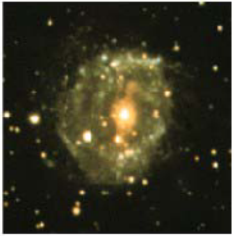
barred spirals



Sa



Sb



Sc

Classification of galaxies

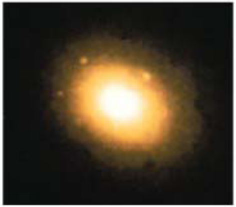
- elliptical galaxies
  - sub-class depends on *apparent* ellipticity

$$\epsilon = 1 - \beta/\alpha$$

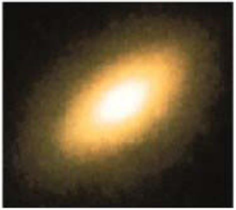
  - sub-class is 10ϵ
  - E7 is "latest" classes, $>$E8 not found so far.
- S0/SB0: intermediate class: *lenticular galaxies*

ellipticals

E0

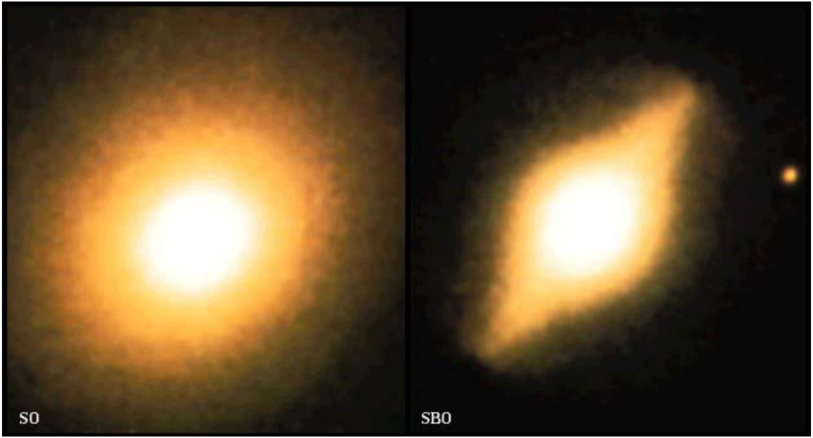


E3



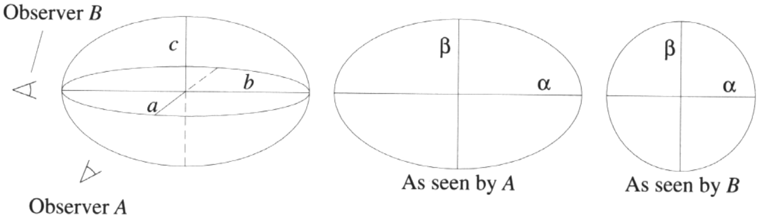
E6

lenticular galaxies



Classification of galaxies

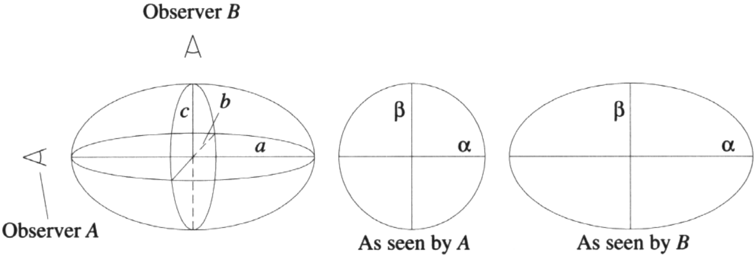
- Class E does *not* use the "real" shape of the galaxy: *oblate spheroidal galaxy*



  - $a = b$
  - $c < a$

Classification of galaxies

- *prolate spheroidal galaxy*



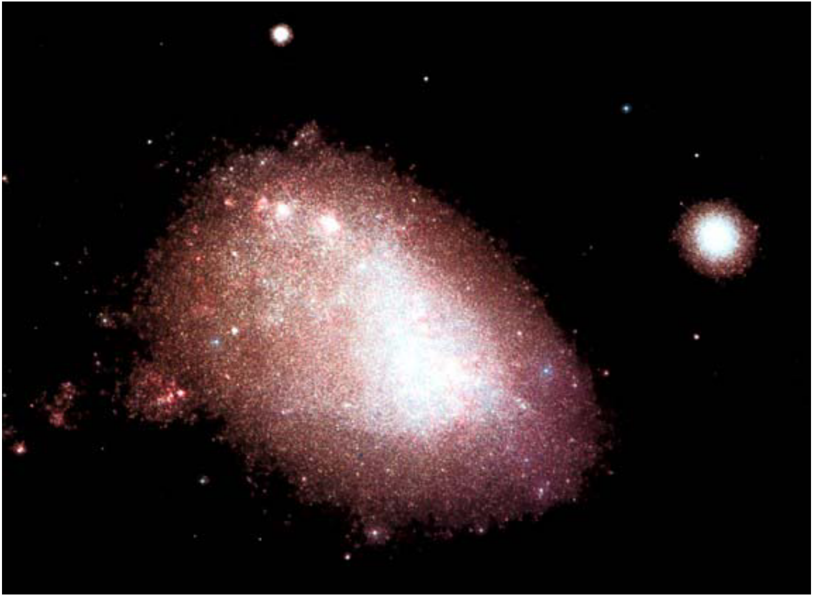
  - $b = c$
  - $a > b$

Classification of galaxies

- irregular galaxies:
  - Irr I: hint of structure (LMC, SMC)
  - Irr II complete chaos

Irr I (LMC)

Irr I (SMC)



Modifications

- *luminosity class*
  - ranges I to V
  - uses “definition” of the arms
  - does *not* correlate well with absolute magnitude!

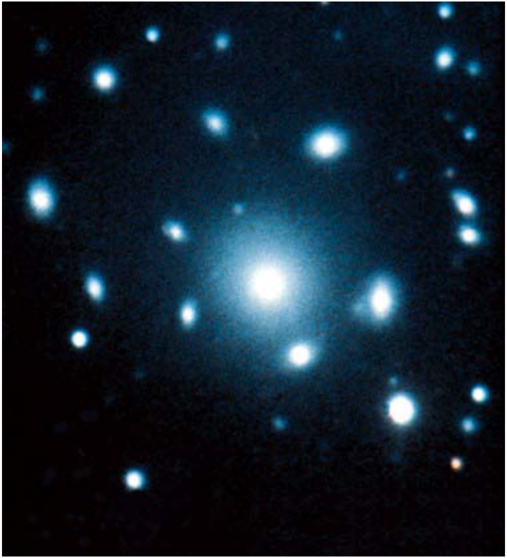
Modifications

- *de Vaucoleurs:*
  - remove Irr I and Irr II, S-classes later than Sc or SBc
  - Irr I → Sd (SBd), Sm (SBm), Im (m: Magellanic type)
  - Irr II → Ir or "amorphous"
  - Sd's and later are very small → *dwarf spirals*

Elliptical galaxies

- modern classification:
  - cD galaxies: huge (1 Mpc) and bright, masses $10^{13}\,M_\odot$, large M/L ratios (750!) $\rightarrow$ large masses of dark matter
  - normal elliptical galaxies: 1 kpc to 200 kpc diameters, $10^8 \ldots 10^{13}\,M_\odot$, M/L: 7 to 100.
  - dwarf ellipticals (dE's): 1 to 10 kpc diameter, $10^7 \ldots 10^9\,M_\odot$
  - dwarf spheroidal galaxies (dSpH's): 0.1 to 0.5 kpc, $10^7 \ldots 10^8\,M_\odot$
  - blue compact dwarf galaxies (BCD's): small unusually blue ellipticals, low M/L (0.1).

giant elliptical



dwarf elliptical

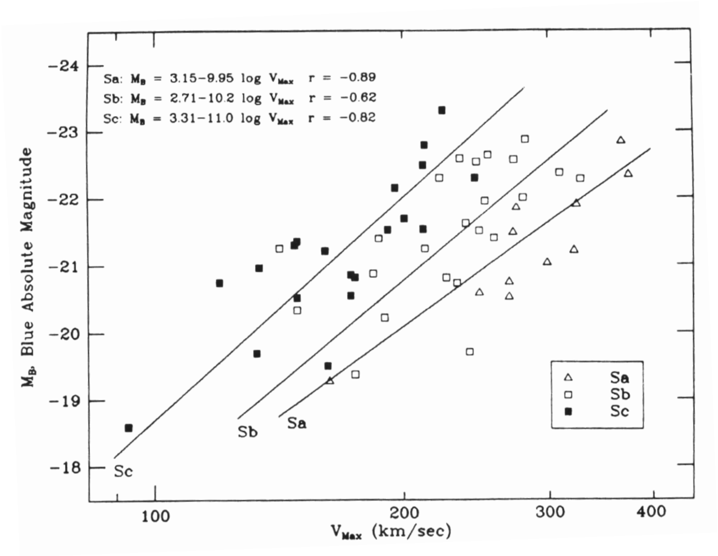
K-correction !!

- extinction correction
- most galaxies show significant redshifts
  $\rightarrow$ light that came, e.g., originally from the B band is shifted away!
- needs to be corrected to get intrinsic B band magnitude!
- $\rightarrow$ K-correction
- more important for more distant galaxies

Tully-Fisher relation !!

- measure rotation speed of galaxies through H I 21 cm line
- maximum rotation velocity $V_{\max}$ correlates with M_B
- different relations for different Hubble-types!
- form depends on distribution of mass within galaxy and mass-to-light ratio!

Tully-Fisher relation !!



Tully-Fisher relation !!

- rotation curve *flat* in the outer parts
- $\rightarrow$ mass contained within distance r from center:

$$M = \frac{V_{\max}^2 R}{G}$$

- with $M/L \equiv 1/C_{\rm ML}$ as the *same* M/L for *all* spirals (assumption!)

$$L = C_{\rm ML} \frac{V_{\max}^2 R}{G}$$

Tully-Fisher relation !!

- if surface brightness is constant for all spirals (another assumption) then $L/R^2 \equiv C_{\rm SB}$
  $\rightarrow$ eliminate R:

$$L = \frac{C_{\rm ML}^2}{C_{\rm SB}} \frac{V_{\rm max}^4}{G^2} \equiv C V_{\rm max}^4$$

Tully-Fisher relation !!

- converting to $M \rightarrow$

$$
\begin{aligned}
M &= M_{\odot} - 2.5\log\left(\frac{L}{L_{\odot}}\right) \\
&= M_{\odot} - 2.5\log V_{\max}^{4} + \text{const.} \\
&= -10\log V_{\max} + \text{const.}
\end{aligned}
$$

- gives the correct leading coefficient in the Tully-Fisher relation

general properties

Table 26-1 Some Properties of Galaxies

	Spiral and barred spiral galaxies	Elliptical galaxies	Irregular galaxies
Mass ($M_\odot$)	10^9 to 4×10^{11}	10^5 to 10^{13}	10^8 to 3×10^{10}
Luminosity ($L_\odot$)	10^8 to 2×10^{10}	3×10^5 to 10^{11}	10^7 to 10^9
Diameter (kpc)	5 to 250	1 to 200	1 to 10
Stellar populations	Spiral arms: young Population I Nucleus and throughout disk: Population II and old Population I	Population II and old Population I	mostly Population I
Percentage of observed galaxies	77%	20%*	3%

* This percentage does not include dwarf elliptical galaxies that are as yet too dim and distant to detect. Hence, the actual percentage of galaxies that are ellipticals may be higher than shown here.

Properties: spirals

- arched lanes of stars (like Milky Way)
- spiral arms contain young, hot stars and H II regions
- $\rightarrow$ Pop. I stars!
- spectrum of a spiral galaxy (sum of all stars!) shows strong metal lines
- central bulge: little star formation, Pop. II stars
- difference related to amount of gas and dust:
  Sa: 4% of mass in gas and dust
  Sb: 8%
  Sc: 25%
- thus Sc has lots of star formation in the disk, Sa doesn't

Properties: barred spirals

- spiral arms start at the ends of a bar running through the nucleus
- subdivided by relative size of central bulge and winding of arms
- SBa to SBc (same idea as for spirals)
- SBa–SBc show similar gas+dust changes as spirals
- bars appear as natural effects in many spirals
- SB's are 2 times more frequent that S's
- models $\rightarrow$ bar does not develop if a massive dark matter halo is present

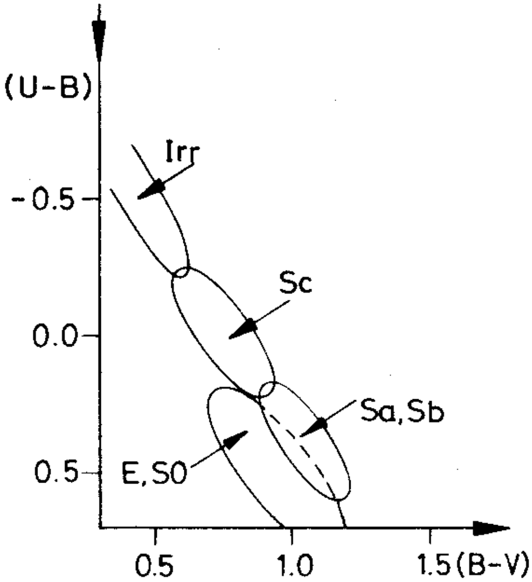
Properties: ellipticals

- practically *no* gas and dust!
- no star formation, only old stars $\rightarrow$ Pop. II stars, red!
- wide range of sizes and masses
- *giant elliptical galaxies*
  - about 20 times larger than normal spiral!
  - pretty rare

Properties: dwarf ellipticals

- much smaller than normal galaxies
- few stars: 10^6 stars (compared to 10^{11} in the Milky Way)
- $\rightarrow$ completely transparent, can see through them
- Doppler shifts of lines $\rightarrow$ stellar motions "random"
- round ellipticals $\rightarrow$ *isotropic* velocities
- flattened ellipticals $\rightarrow$ *anisotropic* velocities

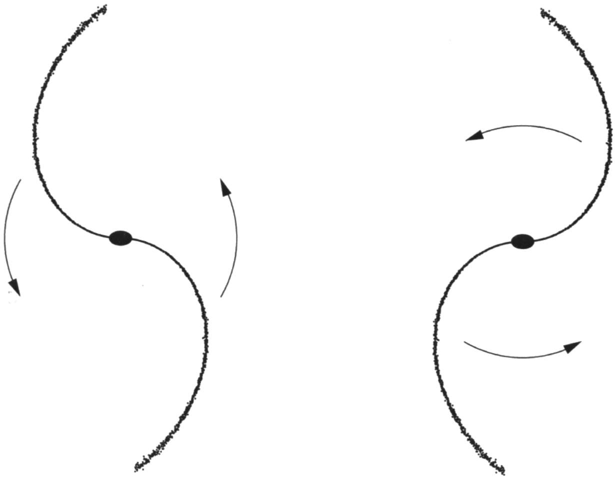
colors



spiral structure !!

- *grand-design spirals*
  - 2 very well defined and symmetric arms
  - 10%
- multiple ($>$ 2 arms) spirals
  - 60%
- *flocculent spirals*
  - ill-defined arms
  - not traceable far from the nucleus
  - 30%

spiral structure



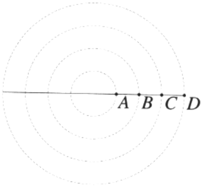
Trailing structure

Leading structure

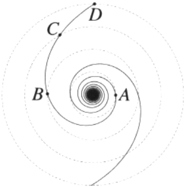
spiral structure

- both leading or trailing spirals are possible!
- radial velocity measurements are ambiguous
- need orientation of the galaxy!
- in almost all feasible cases
  $\rightarrow$ trailing spirals
- some weirdos with $2 + 1$ arm moving in opposite directions
- leading arms caused by tidal interactions?
- *winding problem*

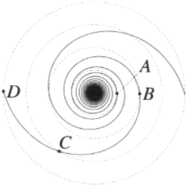
spiral structure !!



(a)



(b)



(c)

spiral structure !!

- differential rotation!
- time scale very short!
- $\rightarrow$ spiral arms are not “constant” pattern of stars

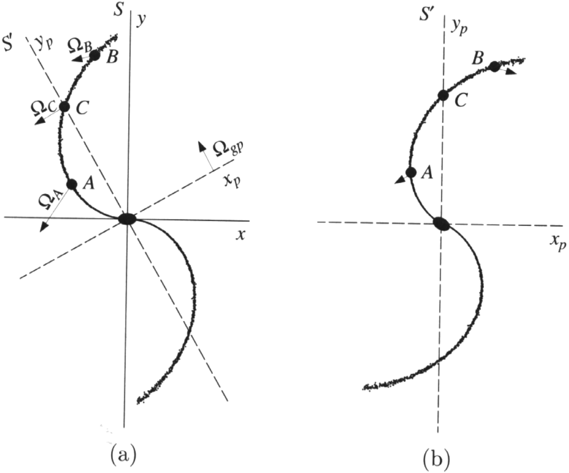
Density Wave Theory !!

- initially proposed by Lindblad
  first worked out by Lin & Shu:
- *quasi-static density waves*
- regions in the disk where density is *larger* than average (10–20%)
- stars, clouds move *through* density waves during orbits around center
- spiral density wave pattern *stationary* in a *non-inertial* rotating coordinate system
- angular speed: *global pattern speed* Ω_{gp}

Density Wave Theory !!

- stars etc. are *not* stationary in this system!!
- near the center: $\Omega > \Omega_{\rm gp}$
  $\rightarrow$ stars *overtake* density wave
- far from the center: $\Omega < \Omega_{\rm gp}$
  $\rightarrow$ density wave overtakes stars
- *Co-rotation radius R_c*: $\Omega = \Omega_{\rm gp}$
  $\rightarrow$ "dividing line"

Density wave theory !!



- S: inertial system, density wave rotates with Ω_{gp}
- S': rotating non-inertial system rotating with Ω_{gp}

Density Wave Theory

- Density wave model explains:
  - young, massive stars in the arms
  - H I and dust in the inner trailing edges of the arms
  - distribution of low mass stars not as concentrated in arms
  - reduces winding problem (but need to stabilize the wave)

Density Wave Theory

- flocculent spirals may be result of several overlapping waves?
  - *SSPF*: stochastic, self-propagating star formation model
  - outbursts of star formation triggered by SNe sequences
  - doesn't explain location of dust and OB stars

Simulation