# Milkway Continues....

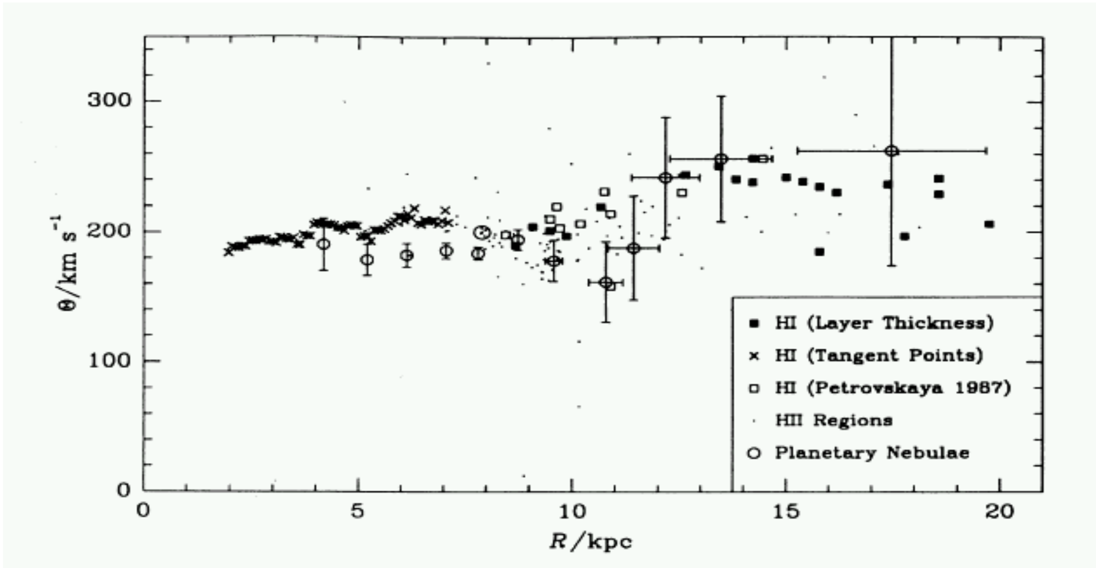


# Mass of MW (Bovy and Tremaine 2012)

- The flatness of the Milky Way's circular-velocity curve at < 20 kpc shows that the visible Galactic disk is embedded in a massive dark halo.
  - The disk is composed of gas and stars (baryons), while the dark halo is dominated by dark matter.
  - unclear if there is substantial amount of dark matter in the disk itself

- One way to determine the local density of dark matter is through a determination of the dependence of the gravitational potential on distance above the mid-plane of the disk ("height"), from measuring the kinematics of stars - a lot more later.
  - But, a major obstacle is that the uncertainty in the amount of baryonic matter in the disk makes it hard to determine the relative contributions from dark and baryonic matter to the density near the mid-plane.
- The contributions from baryonic and dark matter can be disentangled by measuring the gravitational potential out to larger heights. At heights of several times the disk thickness, the dark halo and the baryonic disk contributions to the potential have a different vertical dependence

# MW Rotation Curve

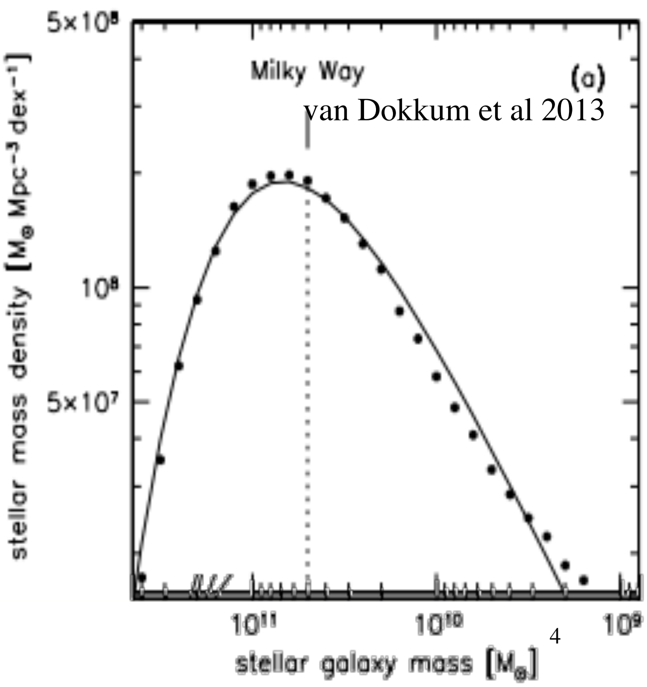



- Flynn, Sommer-Larsen , Christensen 1996



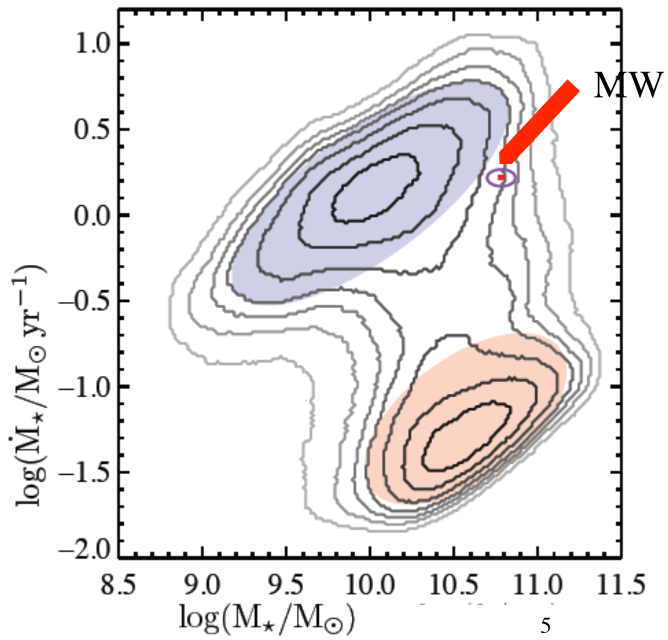
# Stellar Mass of MW compared to Local Galaxy Mass Function

- The stellar mass of the MW is near the peak of the local galaxy mass function (not number density). (notice mass scale runs backwards.... astronomers)



# The MW as Representative of Other Galaxies

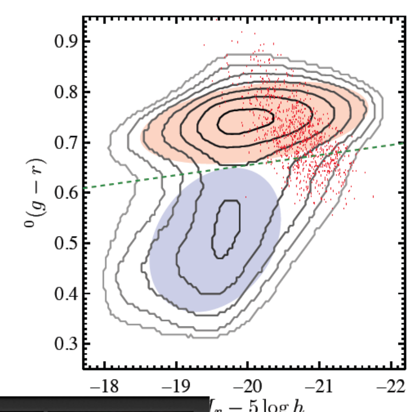
- The MW in comparison with other galaxies (from the SDSS Survey) in the star formation rate vs stellar mass plane
- Copernican assumption that the MW is not extraordinary amongst galaxies of similar stellar mass and SFR.





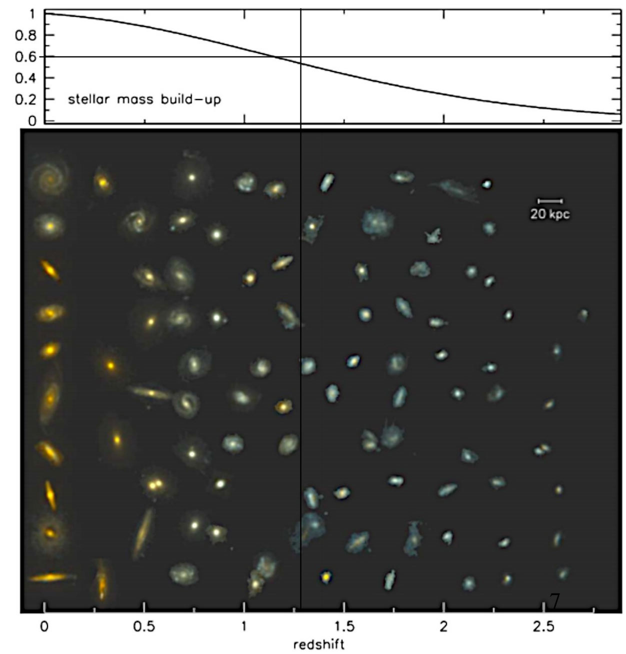

# The MW as Representative of Other Galaxies

- Effects of dust are LARGE
- red dots are MW cognates- what the MW would look like from afar (Licquia and Newman)




# Progenitors of the MW

- What did the progenitors of the MW look like- van Dokkum et al 2013 present images of galaxies with the same mass density of the MW at a variety of redshifts using the average stellar mass buildup as a guide




- organized spirals appear only at z<1
- at higher redshift galaxies had a very different shape
- Galaxies also become redder with time (general drop of SF at low redshift)

# Distribution of Light in Disk (S+G eq 2.8)

the thin disk and the thick disk has a similar form but different scale height and density of stars

**Radial** scale length of a spiral disk

$\Sigma(r)=\Sigma_0\exp(-R/R_d)$**;** integrate over r to get total mass $M_d=2\pi\Sigma_0 R^2_d$

Vertical density distribution is also an exponential $\exp(-z/z_0)$ so total distribution is product of the two

$\rho(R,z)=\rho_0 \exp(-R/R_d)\exp(-z/z_0)$

z= distance above the plane
R= distance from galactic center

$z_0$,$R_d$ are constants describing the galaxy

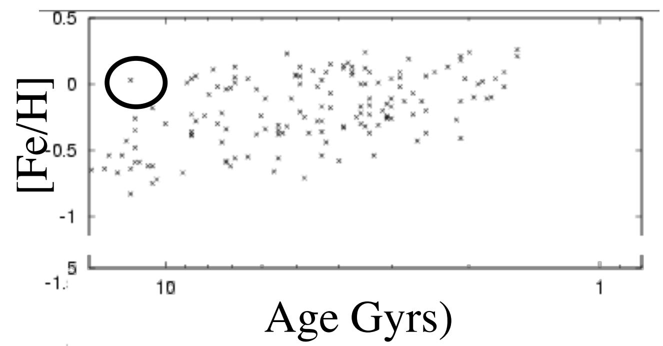
See S&G table 2.1 for more details

# Age Metallicity

- Older stars **tend** to be metal poor: only in the MW and local group can this be studied with great detail   (SG 4.3.2)
- However the metallicity history of the MW is very hard to unfold-recent GAIA +survey data show great complexity.
- Older stars (in the MW) tend to be metal poor
  – logic is that metals are created in SN over cosmic time, next generation of stars is formed from this enriched gas, so more metal rich

•Actually much more complex;

– galaxy is not a closed box, gas flows in and out
  - galaxy mergers can mix things up
– Two types of SN (type I produces mostly Fe, type II mostly O)
– stars can move a long way from their regions of birth
– star formation rate is not constant

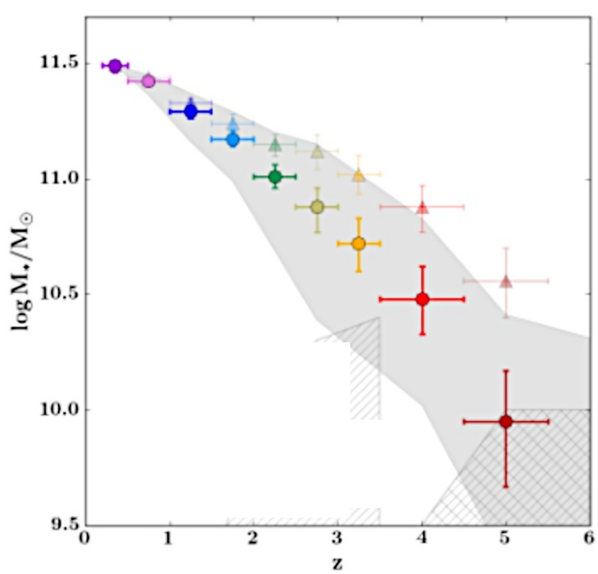



Huge scatter- see http://arxiv.org/pdf/1308.5744.pdf
8.2Gyr old sun like star with Fe/H= -0.013 ± 0.004 and a solar abundance pattern



# How Did the MW Mass Change with Time

- The Milky Way grew via two processes over cosmic time- internal star formation and mergers
  – Figure shows (under 2 assumptions) the mass of a Milky Way progenitor vs redshift. (Hill et al 2017).



## Dynamics and how to use the orbits of stars to do interesting things

**c**

**READ S&G Ch 3 sec 3.1, 3.2, 3 .4**

***we are skipping over epicycles***

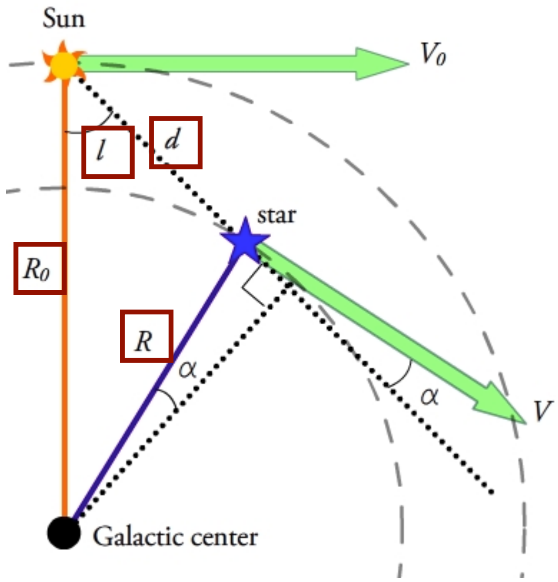


## Galactic Rotation S&G Sec 2.3

- The majority of the motions of the stars in the MW is rotational
- Prime way of measuring mass of spiral galaxies
- map out the distribution of galactic gas
- strong evidence for dark matter

# Galactic Rotation- S+G sec 2.3, B&T sec 3.2

- Consider a star in the midplane of the Galactic disk with Galactic longitude, l, at a distance d, from the Sun. Assume circular orbits radii of R and $R_0$ from the galactic center and rotational velocities of V and , $V_0$
- The 2 components of velocity- radial and transverse are then for circular motion
- $V_{observered, radial}$=V(cos α)-$V_0$sin(l)
- $V_{observered ,tang}$=V(sin α)-$V_0$ cos(l)
- using the law of sines
- sinl/R~ cosα/$R_0$




wikipedia



# Galactic Rotation

- Then using a bit of trig

R(cos α)= $R_0$sin(l)

R(sin α)= $R_0$cos(l)-d

so

$V_{observered,radial}$=(ω- $\omega_0$) $R_0$sin(l)

$V_{observered,tang}$=(ω- $\omega_0$) $R_0$cos(l)-ωd

then following the text expand (ω- $\omega_0$) around $R_0$ and using the fact that most of the velocities are local e.g. R-$R_0$ is small and d is smaller than R or $R_0$ (not TRUE for HI) and some more trig

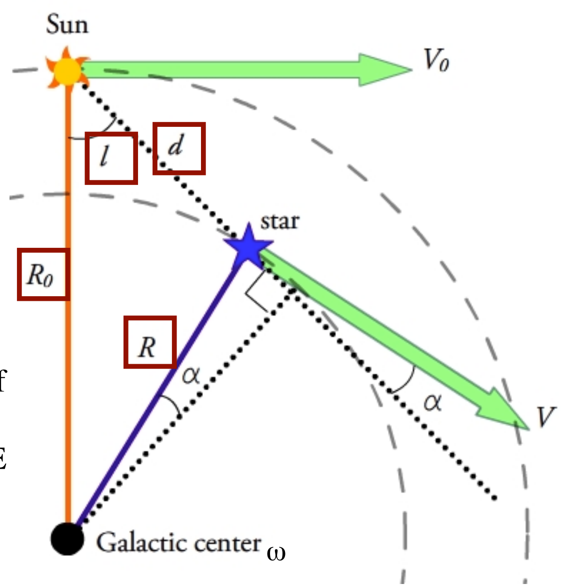
get

$V_{observered,radial}$=Adsin(2l);$V_{obs,tang}$=Adcos(2l)+Bd

Where

A=-1/2 $R_0$dω/dr at $R_0$

- B=-1/2 [($R_0$dω/dr) –ω] $\omega_0$= $V_0$/$R_0$



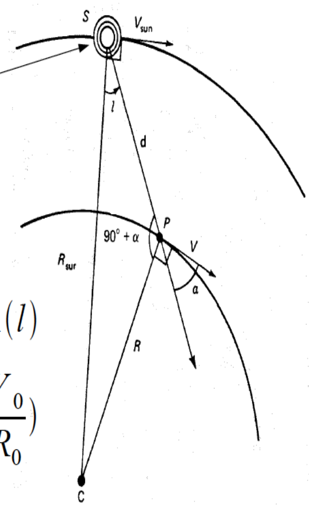
# Galactic Rotation Curve- sec 2.3.1 S+G

Assume gas/star has a perfectly circular orbit

At a radius $R_0$ orbit with velocity $V_0$; another star/ parcel of gas at radius R has a orbital speed V(R)

since the angular speed V/R drops with radius V(R) is positive for nearby objects with galactic longitude 0 <l<90 etc etc (pg 91 bottom)

- Galactic Rotation Curve
  - At $R_{sun}$ the lsr has a velocity of $V_0$
  - A star at P has an apparent velocity of

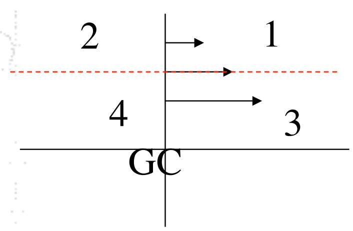



1) $V_r = V\cos(\alpha) - V_0\sin(l)$

2) $V_r = R_0\sin(l)\left(\frac{V}{R} - \frac{V_0}{R_0}\right)$

- Convert to angular velocity $\omega$
- $V_{observered,radial} = \omega R(\cos\alpha) - \omega_0 R_0 \sin(l)$
- $V_{observered,tang} = \omega R(\sin\alpha) - \omega_0 R_0 \cos(l)$



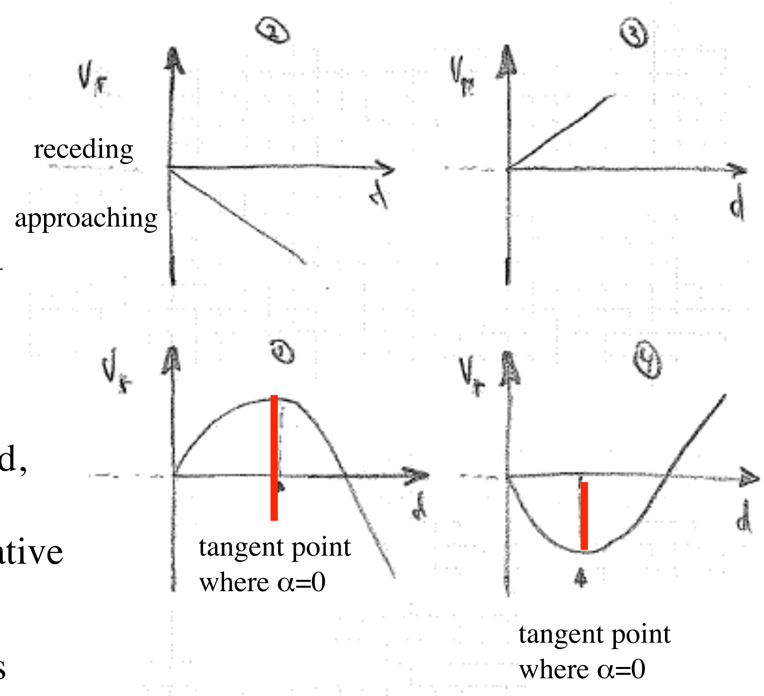



(1) 0<l<90

(2) 90<l<180-larger d, $R>R_0$ $\omega<\omega_0$- increasingly negative radial velocity

(3) 180<l<270- $V_R$ is positive and increase with d

(4) 270<l<360



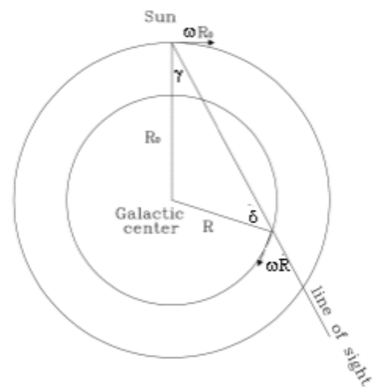

Veilleux 2010

# In terms of Angular Velocity

- Model Galactic motion as circular motion with monotonically decreasing angular rate with distance from center.
- Simplest physics: if the mass of the Galaxy is <u>all at center</u> angular velocity $\omega$ at R is $\omega=M^{1/2}G^{1/2}R^{-3/2}$
- If looking through the Galaxy at an angle $l$ from the center, velocity at radius R projected along the line of site minus the velocity of the sun projected on the same line is
- $V = \omega R \sin \delta - \omega_o R_o \sin l$
  - $l$ is galactic longitude (in figure this is angle $\gamma$)
- $\omega$ = angular velocity at distance R

  $\omega_o$ = angular velocity at a distance $R_o$ (e.g. the sun)

  $R_o$ = distance to the Galactic center




- Using trigonometric identity $\sin d = R_o \sin l / R$ and substituting into equation (1)
- $V = (\omega - \omega_o) R_o \sin l$

http://www.haystack.mit.edu/edu/undergrad/srt/SRT Projects/rotation.html



# Continued

- The tangential velocity $v_T = V\sin\alpha - V_o \cos l$ and $R\sin\alpha = R_o \cos l - d$
- a little algebra then gives

  $V_T = V/R(R_o \cos l - d) - V_o \cos l$
- re-writing this in terms of angular velocity
- $V_T = (\omega - \omega_o) R_o \cos l - \omega d$; $V_T$ is the maximum velocity along a line of sight

- For a reasonable galactic mass distribution we expect that the angular speed $\omega = V/R$ is monotonically decreasing at large R (most galaxies have flat rotation curves (const V) at large R) then get a set of radial velocities as a function of where you are in the galaxy

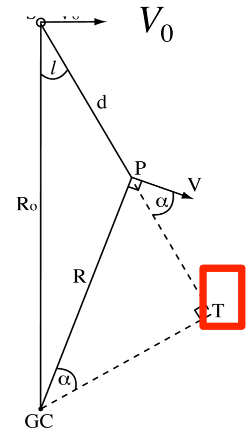
- $V_T$ is positive for $0<l<90$ and nearby objects- if $R>R_0$ it is negative
- For $90<l<180$ $V_T$ is always negative
- For $180<l<270$ $V_T$ is always positive (S+G sec 2.3.1)

# Tangent Point Method

- the *tangent-point method* allows us to find the rotation curve using HI data.
- The angular speed $V/R$ drops

with radius. So when we look out in the disk along a fixed direction with $0 < l < 90°$, the radial speed $V_r(l, R)$ is greatest at the tangent point T where the line of sight passes closest to the Galactic center.

- we have $R = R_0 \sin l$ and $V(R) = V_r + V_0 \sin l$ *eq* (2.17)
- Thus, if there is emitting gas at virtually every point in the disk, we can find $V(R)$ by measuring in Figure 2.20 the largest velocity at which emission is seen for each longitude $l$;



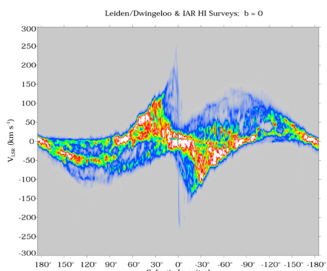
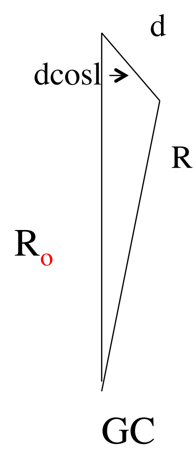



Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



# Oort Constants S&G pg 92-93 sec 2.3.1




## Derivation:

•for objects near to sun, use a Taylor series expansion of $\omega-\omega_o$

$\omega-\omega_o = d\omega/dR$ evaluated at R and $R_o$

$\omega = V/R$; $d\omega/dR = d/dr(V/R) = (1/R)dV/dr - V/R^2$

then to first order

$V_r = (\omega-\omega_o)R_o \sin l = [dV/dr - V/R](R-R_o) \sin l$ ; when $d \ll R_o$

$R-R_o = d\cos l$ which gives

$V_r = (V_o/R_o - dV/dr)d \sin l \cos l$

using trig identity $\sin l \cos l = 1/2 \sin 2l$

one gets the Oort formula

$V_r = Ad\sin 2l$

$$A = \frac{1}{2}\left[\frac{V_o}{R_o} - \left(\frac{dV}{dR}\right)_{R_o}\right]$$

# Oort Constants

- For nearby objects ( d<<R) then (l is the galactic longitude)
  - $V(R) \sim R_0 \sin l\,(d(V/R)/dr)(R-R_0)$ $\sim d\sin(2l)[-R/2(d(V/R)/dr) \sim d$**A**$\sin(2l)$
- A is one of 'Oorts constants'
- The other (pg 93 S+G) is related to the tangential velocity of a object near the sun $V_t = d[A\cos(2l)+B]$
- So, stars at the same distance r will show a systematic pattern in the magnitude of their radial velocities across the sky with Galactic longitude.
- A is the Oort constant describing the shearing motion and B describes the rotation of the Galaxy

$$A = \frac{1}{2}\left[\frac{V_o}{R_o} - \left(\frac{dV}{dR}\right)_{R_o}\right]$$

$$B = -\frac{1}{2}\left[\frac{V_o}{R_o} + \left(\frac{dV}{dR}\right)_{R_o}\right]$$

$$A+B = -\left(\frac{dV}{dR}\right)_{R_o} \quad ; \quad A-B = \frac{V_o}{R_o}$$

$A=-1/2[Rd\omega/dr]$

Useful since if know A get kinematic estimate of d

Radial velocity $v_r \sim 2AR_0(1-\sin l)$ only valid near $l \sim 90$ measure$_{21}$ $AR_0 \sim 115 km/_s$

# Oort 'B'

- B measures 'vorticity'
- $B=-1/2R[(d\omega/dr)+(2\omega/R)]=-1/2[(V/R)+(dV/dR)]$ angular momentum gradient

**$\omega=A-B=V_0/R_0$**; angular speed of Local standard of rest (sun's motion)

A express local shear, B local 'vorticity'

Oort constants are local description of differential rotation

Needed measurement

- Measuring Oort'sConstants Requires measuring $V_R$, $V_T$, and d
- $V_R$ – easy , $V_T$ hard because you need to measure proper motion
- $\mu$(arcsec/yr) = $V_T$(km/s)/d (pc) (do the calculation !)

A=14.8 km/s/kpc B=-12.4 km/s/kpc

**Velocity of sun $V_0=R_0(A-B)$;**

**(A-B)=27km/s/kpc: Period of sun $P(R_0) = 2\pi/(\omega(R_0) = 2\pi/27.2 Gyr^{-1}$**

**(A+B)=2.4km/s/kpc;, rotation curve is flat near the sun**

# A Guide to the Next Few Lectures

•The geometry of gravitational potentials : methods to derive gravitational potentials from mass distributions, and visa versa.

•Potentials define how stars move

•The gravitational field and stellar motion are interconnected : the Virial Theorem relates the global potential energy and kinetic energy of the system.

• Collisions?

• The Distribution Function (DF) : the DF specifies how stars are distributed throughout the system and with what velocities.

For collisionless systems, the DF is constrained by a continuity equation : the Collisionless Boltzmann Equation

•This can be recast in more observational terms as the Jeans Equation.

The Jeans Theorem helps us choose DFs which are solutions to the continuity equations