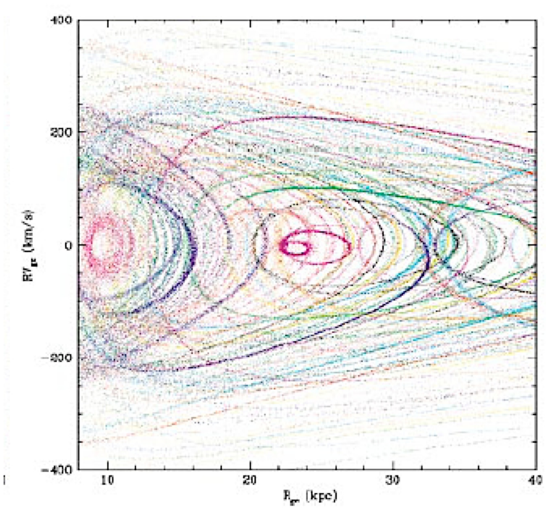
MW II

- Use of gas (HI) to trace velocity field and thus mass of the disk (discuss a bit of the geometry details in the next lecture)
  - dependence on distance to center of MW
- properties of MW (e.g. mass of components)

- Cosmic Rays – only directly observable in MW
- Start of dynamics

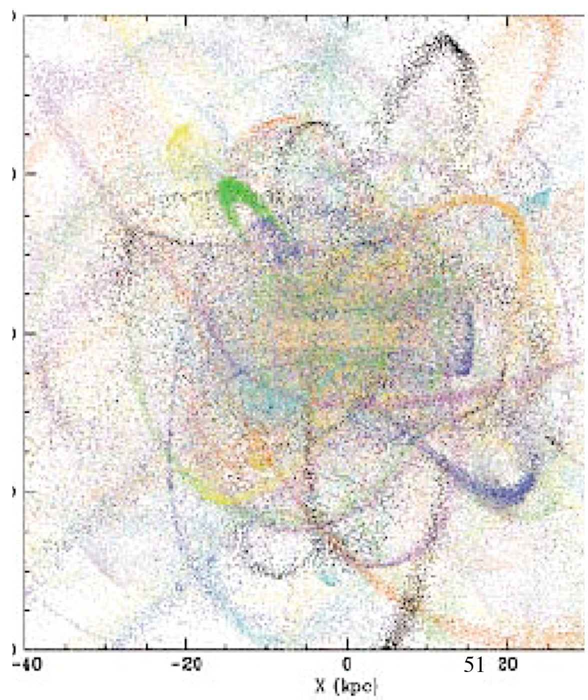
Theorists View of MW Stars Orbits

- Each merged galaxy is a separate color (Freeman and Bland-Hawthorn)



radial velocity vs orbital radius

position of stars in x,z plane



Timescales

- crossing time $t_c=2R/\sigma\sim5\text{x}10^7$yrs (R_{10kpc}/v_{200})

- dynamical time $t_d=\text{sqrt}(3\pi/16G\rho)$- related to the orbital time; assumption homogenous sphere of density ρ

- **Relaxation time**- the time for a system to 'forget' its initial conditions

$t_r\sim Nt_c/48f^2$: N objects carrying fraction ,f, of total mass :

S+G (eq. 3.55) gives

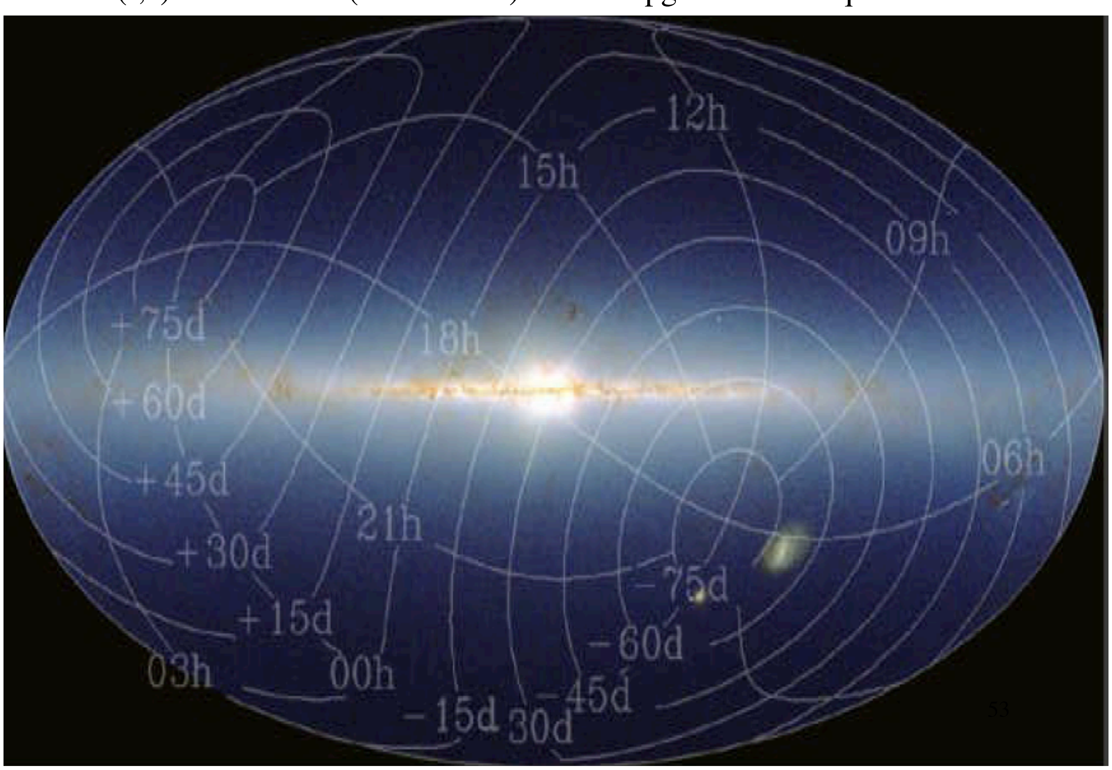
$t_r=V^3/8\pi G^2m^2n\ln\Lambda\sim2\text{x}10^9\text{yrs}/[(V/10\text{km/sec})^3(m/M_\odot)^{-2}(n/10^3\text{pc}^{-3})^{-1}$

major uncertain is in $\ln\Lambda-$ numerical simulations ~20

mass of stars is M

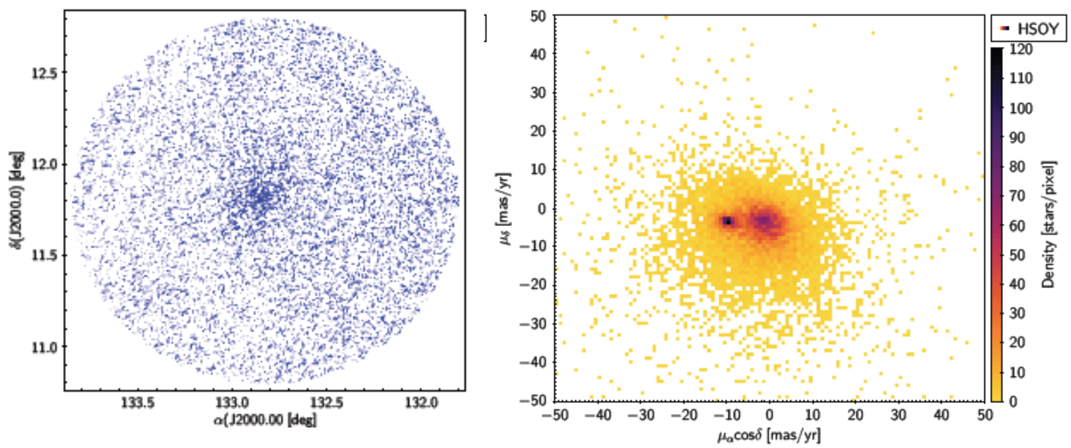
Coordinate Systems

- Galactic (l,b) and celestial (Ra and Dec) see S+G pg 34-37 for a quick refresher



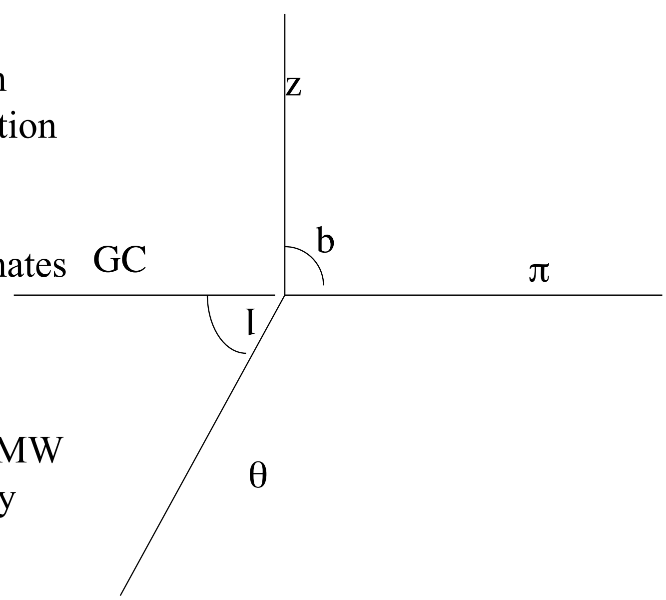
Early GAIA Results

- Proper motions in the M67 star cluster-accuracies of ~5mas/year ($5x10^{-9}$ radians/year or $4.3x10^{-5}$ pc/year at distance of M67)



Coordinate Systems

The stellar velocity vectors are
z: velocity component
  perpendicular to plane
θ: motion tangential to GC with
  positive velocity in the direction
  of rotation
π: radial velocity wrt to GC
With respect to galactic coordinates
+π= (l=180,b=0)
+θ= (l=30,b=0)
+z= (b=90)
Local standard of rest: assume MW
  is axisymmetric and in steady
  state
$(\pi,\theta,z)LSR=(0,\theta_0,0)$;

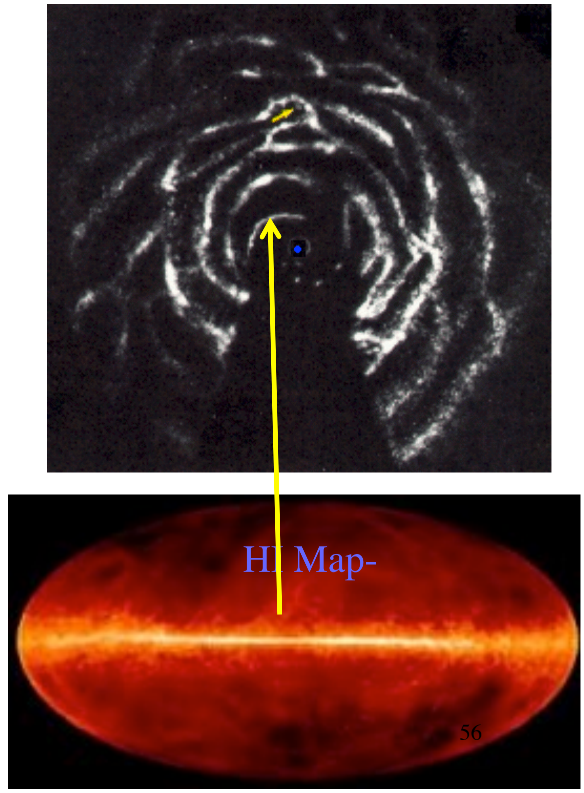


HI Maps- Major Way to Trace MW Velocity Field

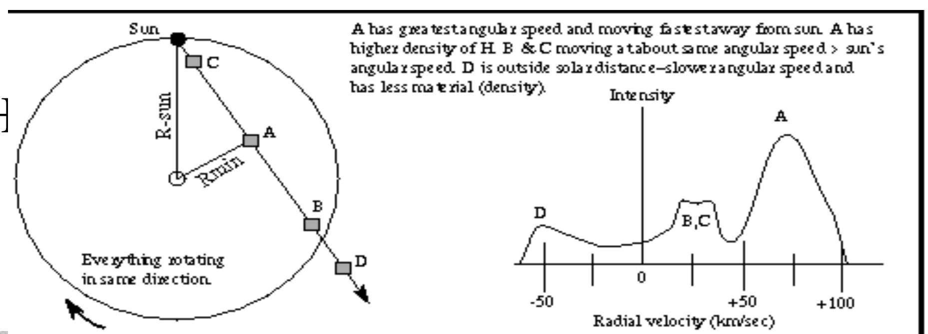
- HI lies primarily in the galactic plane- maps have velocity data associated with them- allows dynamics to be determined
  - deproject HI velocity and intensity map to show total structure of the galaxy
- Not affected by dust- shows detailed structures.

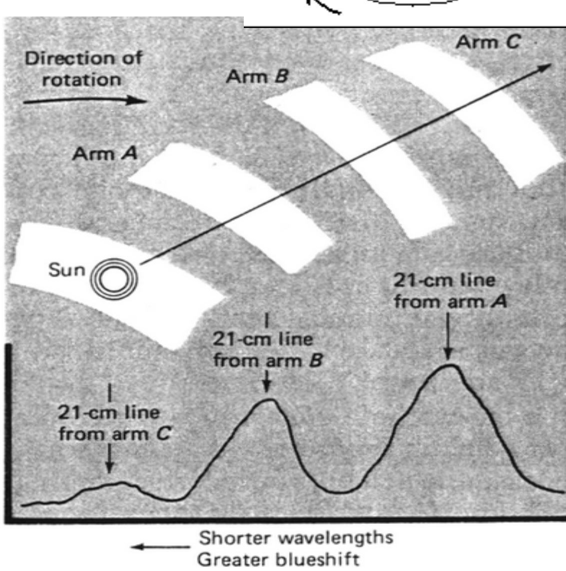
Neutral atomic hydrogen (HI) traces the interstellar medium (ISM) over a broad range of physical conditions.

- 21-cm emission line is a key probe of the structure and dynamics of the Milky Way Galaxy.



Using H





Observed radial velocity of the cloud will be the difference between the Suns component of MW Rotation and the cloud along the line of sight

$V_r = V\cos\alpha - V_{sun} \sin l$

Velocity of HI

- In the plane of the disk the velocity and intensity of HI gas (Sparke and Gallagher fig 2.20)
- The distribution of HI and CO emission in the longitude-velocity plane yield a characteristic maximum ("terminal") velocity for each line of sight
- The terminal velocities are related to the circular speed $v_c(R)$ by (ℓ=galactic longitude)

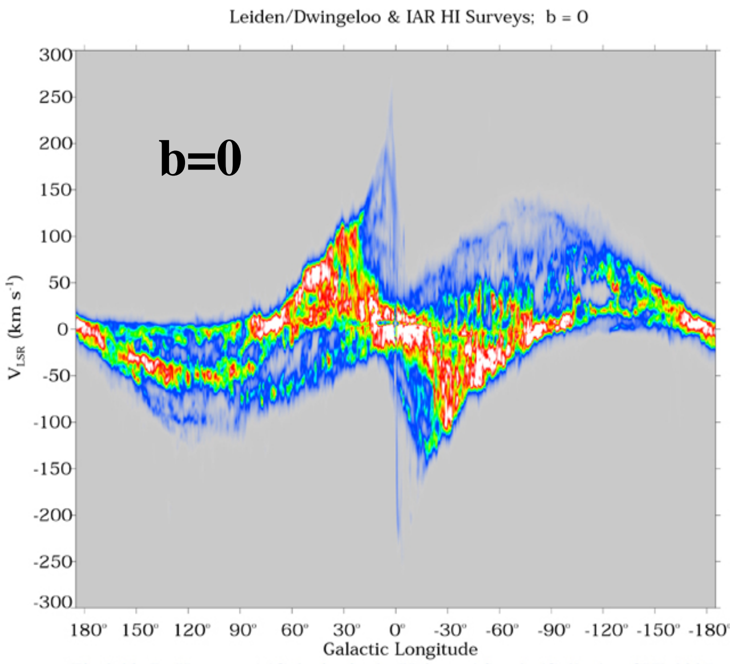


Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

$$\boxed{v_{term}(\ell) = ((\sin\ell)\, v_c(R) - v_c(R_0))\sin\ell}$$

HI Observables- How to 'De-project' to Determine Dynamics S& G 2.31

- Assume that most of the gas follows an axisymmetric circular rotation gives a relation for the differential rotation velocity (e.g., Burton1988)
  $v(R, z)=[(R_\odot/R)\ \Theta(R, z)-\Theta_\odot]\sin(\ell)x\cos(b)$ where v is the radial velocity along a line of sight (directly measurable); and Θ is the tangential velocity
- $V_r = R_0 \sin l[V/R - V_0/R_0]$; V_0 velocity of sun R_0 distance of sun from center of MW
- for $R < R_\odot$, distances are ambiguous,
- for $R > R_\odot$, one needs to know the Galactic constants $R_\odot$ and $\Theta_\odot$ and the form of $\Theta(R, z)$ e.g. the rotation curve shape.
- See S&G pg 92-94.

$R_\odot$ is the distance of the sun from the galactic center and $\Theta_\odot$ is the velocity of rotation at the sun (a lot more later)

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

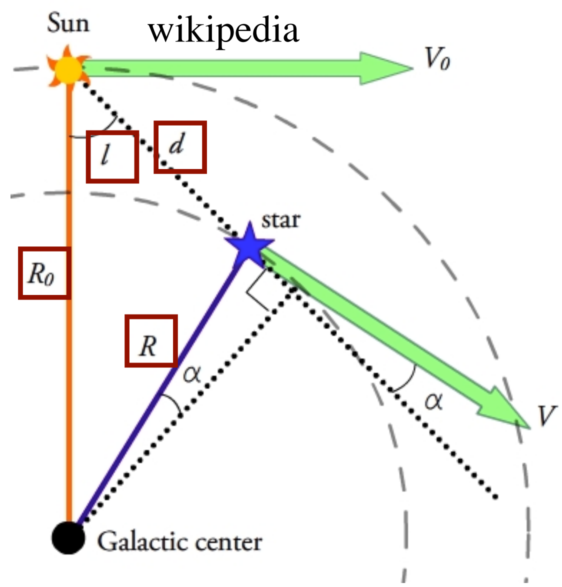
- The 2 components of velocity- radial and trangential are for circular motion
- $V_{\text{observered, radial}}=V(\cos\alpha)-V_0\sin(\ell)$
- $V_{\text{observered ,tang}}=V(\sin\alpha)-V_0\cos(\ell)$
- using the law of sines

$\sin\ell/R\sim\cos\alpha/R_0$

which gives

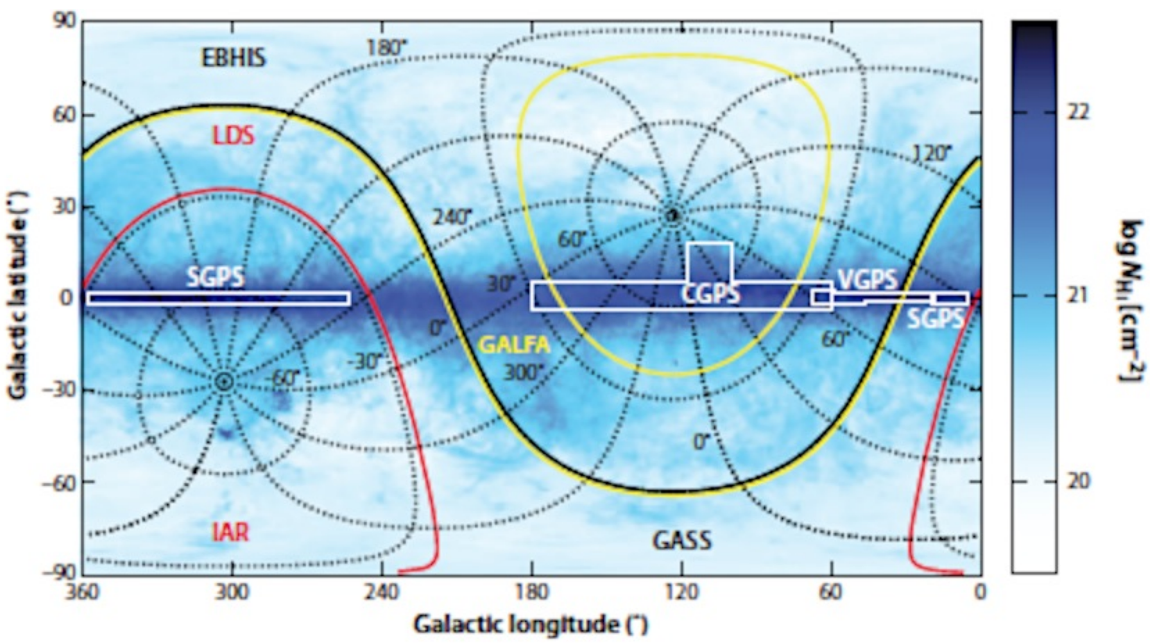
$V_{\text{observered, radial}}=R_0\sin(\ell)[(V/R)-(V_0/R_0)]$
S&G 2.11

Much more later



Since we have 'poor' idea of distance rely on tangent point
at 0<l<90 radial velocity is highest at the tangent point where los passes closest to galactic center

HI Intensity Map

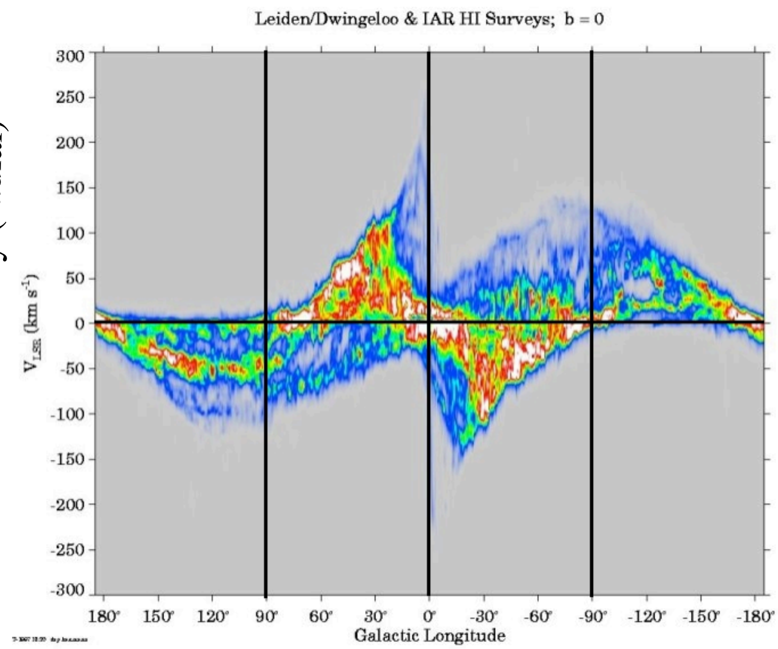


- Acronyms are the names of different surveys
- Dotted lines are ra and dec coordinates

Galactic Rotation Curve HI data

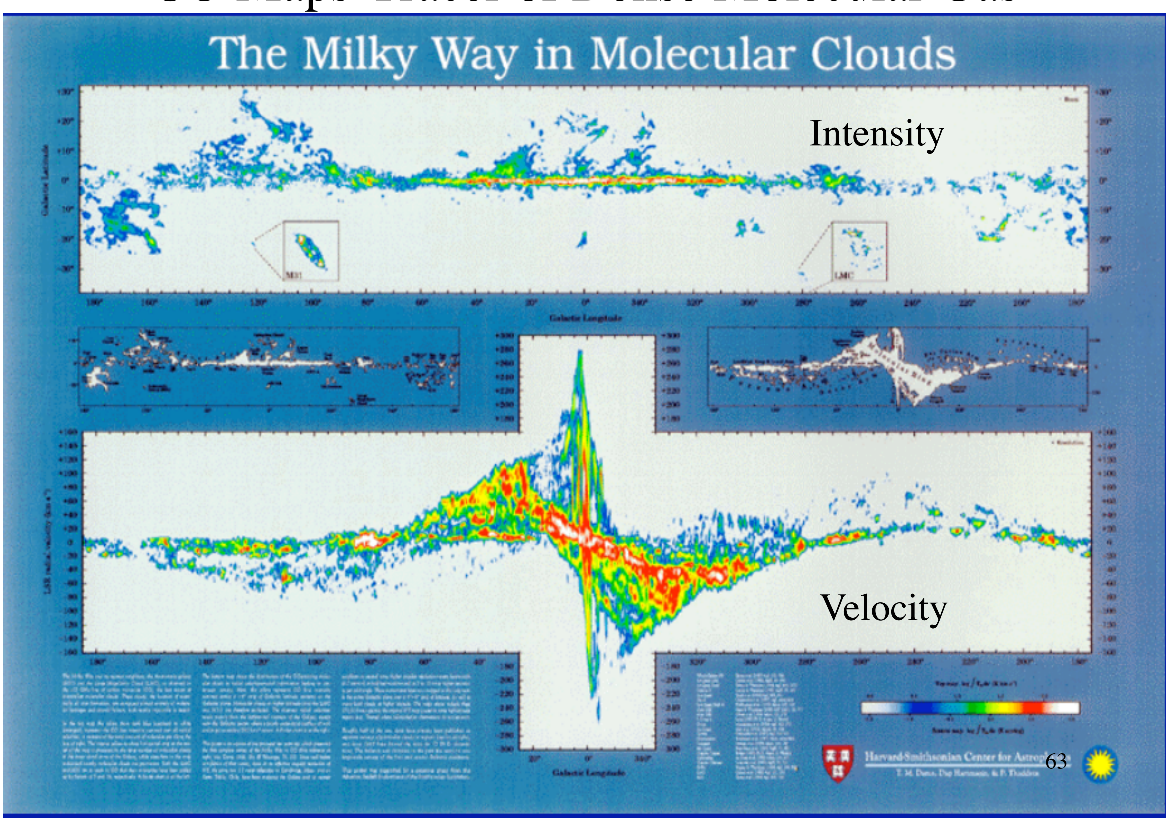
- Velocity, longitude, intensity graph of HI in the MW fig 2.20 in S+G
- The HI probes very large scales and **so many of the approximations in the derivation of the Oort constants (S+G pg 92-93) (see next lectures) are not correct and one must use the full up equations.**

Velocity (radial)



Galactic Longitude

CO Maps-Tracer of Dense Molecular Gas

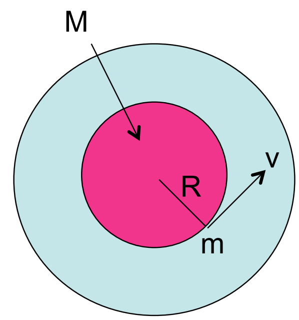


Differential Rotation

$$M(R) = \int_0^R \rho(r)\, dV$$

Motion at distance *R* from center depends only on *M(R)*
The mass behaves as if it were centrally concentrated (Newton)

For an object with mass *m at* R, gravity must balance acceleration of circular motion



$$GM(R)m/R^2 = mv^2/R$$
$$M(R) = v(R)^2R/G$$

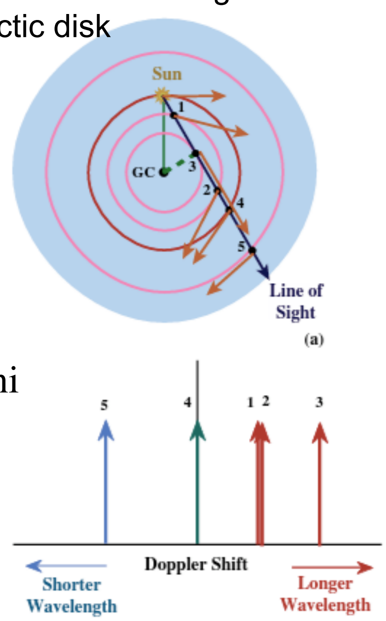
Measure *v(R)* to get *M(R)*

Let $\omega(R) = v(R)/R$, then
$$M(R) = \omega(R)^2R^3/G$$

v(R) or *ω(R)* gives the *rotation curve* of the Galaxy.

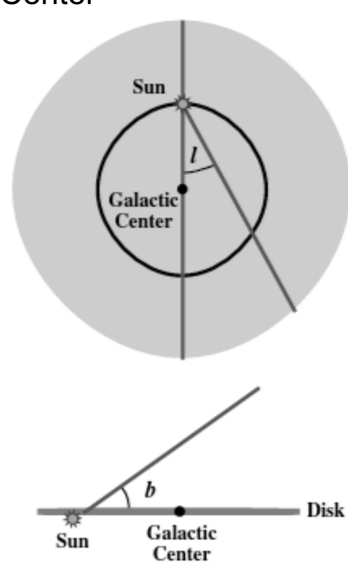
Differential Rotation

Differential galactic rotation produces Doppler shifts in emission lines from gas in the Galactic disk



Sarajadini

Define Galactic Coordinates
b = galactic latitude in degrees above/ below Galactic disk
l = galactic longitude in degrees from Galactic Center

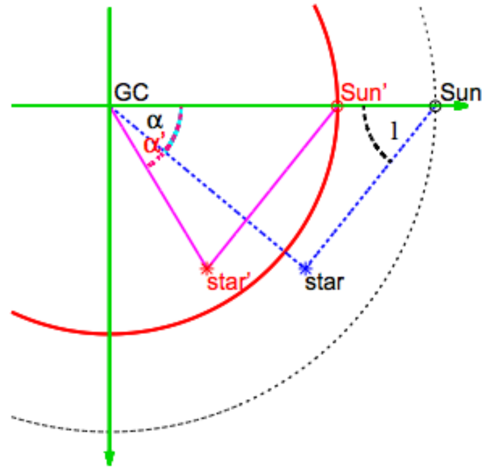


Why Rotation Curves for MW Depend on R_0

Changing R_0's effect on determination of the rotation curve

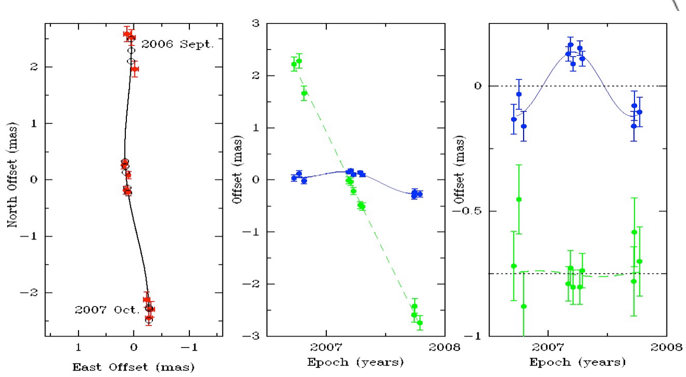
- Since the galactic longitude of the object (star, gas) does not change (as change R_0), the angle, α, must grow as R_0 lessens
- This reduces the rotation speed estimated from the sources radial velocity

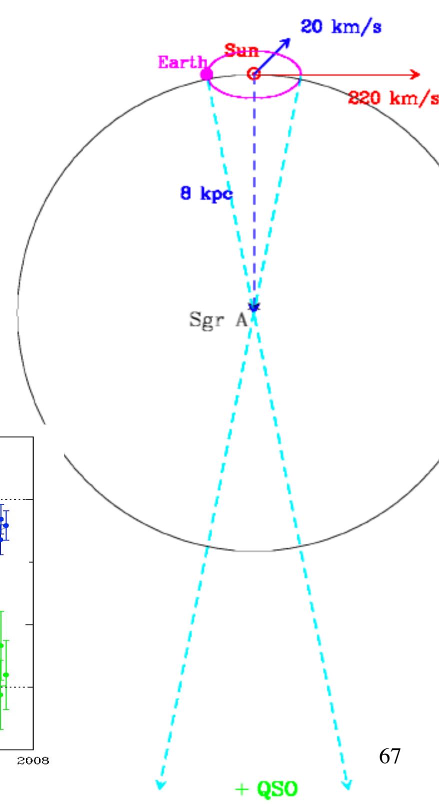
R. Schonrich



Distances From Motions

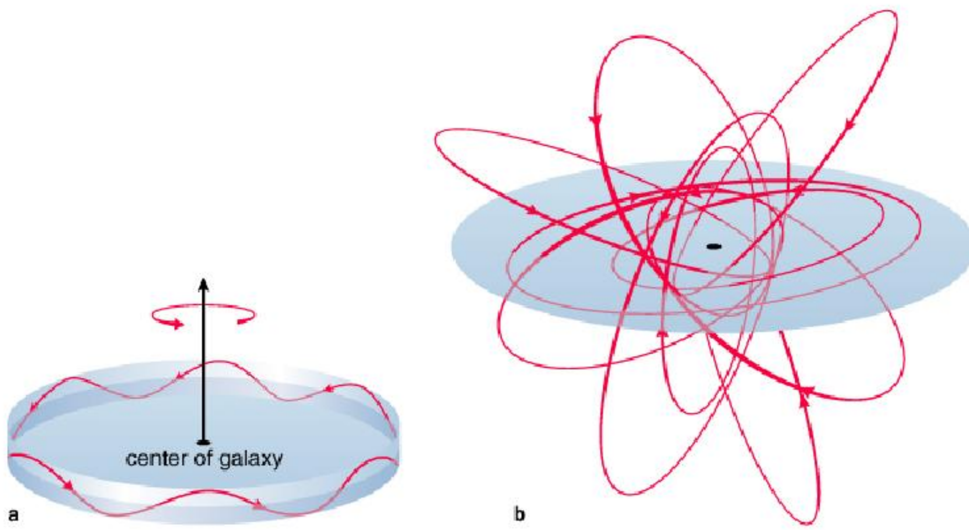
- Distance to the galactic center (R_0) is rather important; problem 2.6 (S&G) discusses one way to use the observed positions and velocities of stars in orbit around the galactic center to get the distance
- Another way of doing this: measure the proper motion+parallax of SgrA* caused by the velocity of the sun
- East in blue, north in green -right panel has proper motion removed. left panel motion on sky



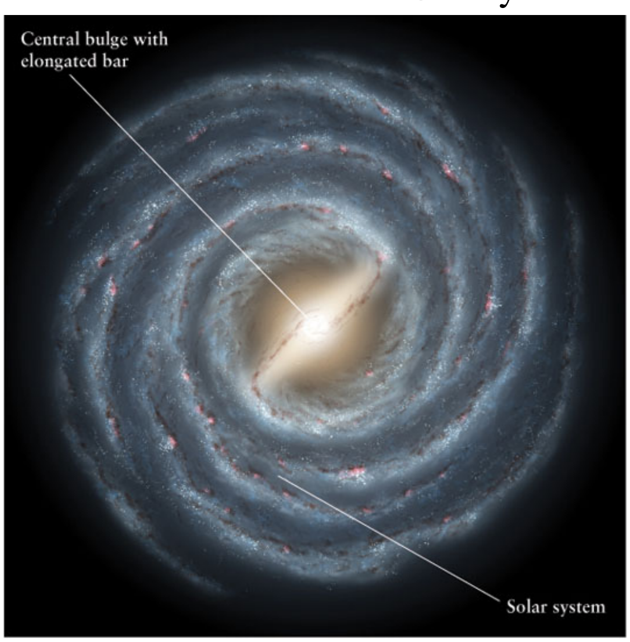


Zeroth Order Dynamics

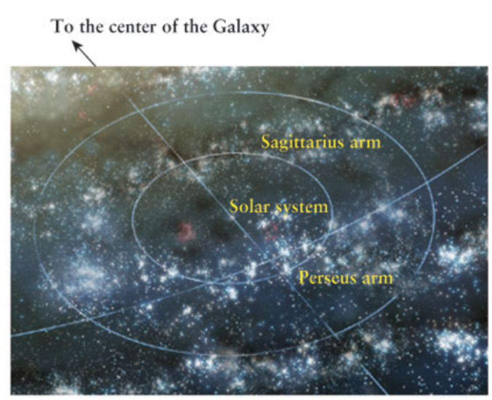
- Stars in disk have mostly rotational velocity- very little random or r or z components
- Stars in bulge and halo mostly random orbits, but some rotation.
- Need to use different techniques to estimate the mass of these '2' components



MW is a Barred Galaxy



(a) The structure of the Milky Way's disk



(b) Closeup of the Sun's galactic neighborhood

The MW bar, consists of relatively old red stars,
roughly 9 kpc in length
oriented at about a
45-degree angle relative to a line joining the sun
and the center of the galaxy

Basic Properties of MW

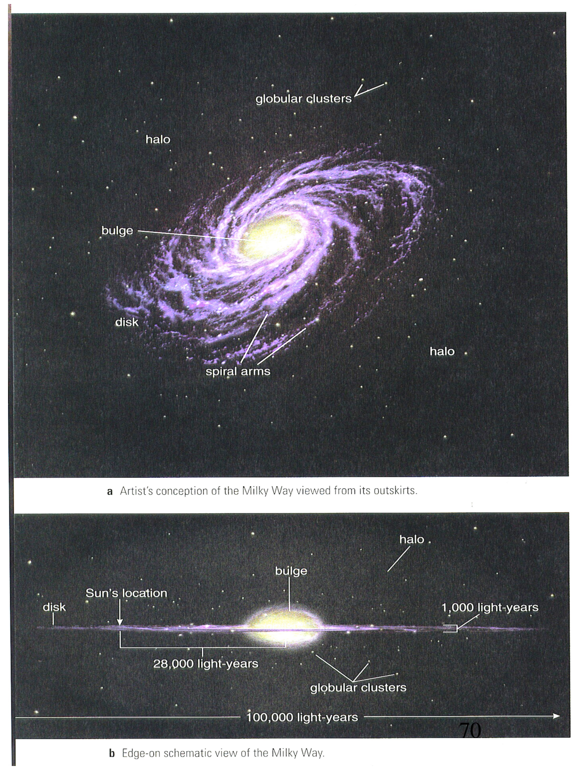
Diameter ~23Kpc (ill defined)
at sun orbital period ~2.5×10^{8} yrs
Mass ~2×10^{11} $M_\odot$ (details later)
M/L_V~10-15, ~2 for stars (including DM)
Official distance of sun from GC is 8.5kpc,
$v_{circular}$~220km/sec

Perpendicular to the disk the stellar distribution(s) can each be 'well' described by

$n(z) \sim \exp(-z/h)$; h=scale height

The disk is NOT simple and has at least 2 components

1) thin disk - largest fraction of gas and dust in the Galaxy, and star formation is taking place ; h~100pc, σ_z~20km/sec
2) thick disk h~1.5 kpc older, lower metallcity population, less gas- only makes up 2% of mass density **at z~0**.

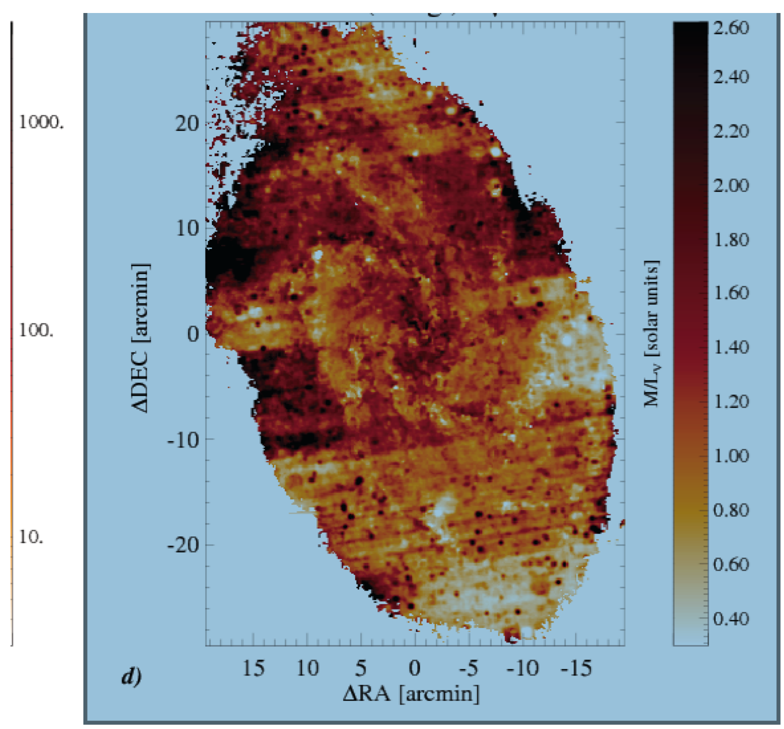


a Artist's conception of the Milky Way viewed from its outskirts.

b Edge-on schematic view of the Milky Way.

M/L_V in Nearby Galaxy M33

- M/L_V of the stars



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

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

while we may know the scale length of the stars, that of the dark matter is not known.

Also the nature of the dark matter halo is not known:- disk/halo degeneracy

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

z_0, R_d are constants describing the galaxy

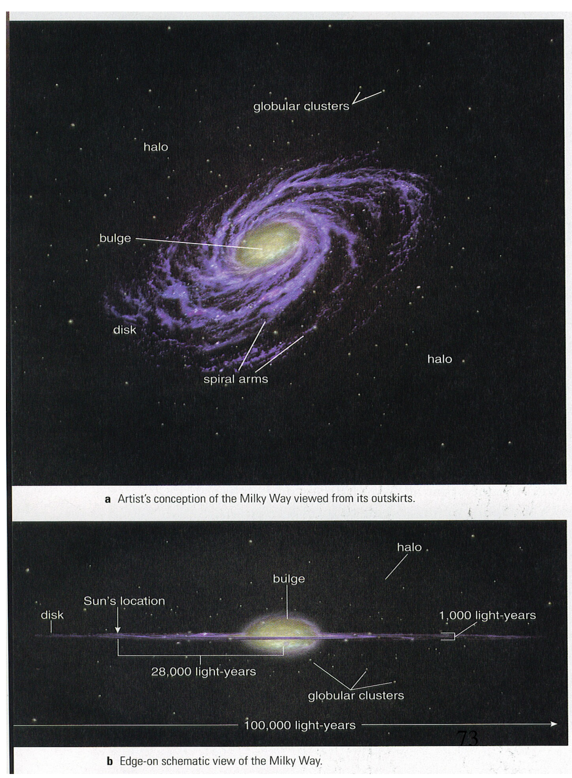
See S&G table 2.1 for more details

Components of MW

HII scale height: 1 kpc
CO scale height: 50-75 pc
HI scale height: 130-400 pc
Stellar scale height: 500 pc in disk
Stellar mass: $\sim 5\times10^{10}\, M_\odot$
HI mass: $\sim 3\times10^9 M_\odot$
H_2 mass (inferred from CO mass):$\sim 0.8\times10^9 M_\odot$

Total MW mass within viral radius is $\sim 8\times10^{11} M_\odot$: Mostly DM

The mass values depend on the radius within which they are estimated



a Artist's conception of the Milky Way viewed from its outskirts.

b Edge-on schematic view of the Milky Way.

Mass Distribution near Sun

- The (surface) density distributions can be derived from dynamical studies (much more later in class)

- The total surface mass density of all gravitating matter within 1.1 kpc of the centerline of the disk at the position of the sun is 67 +/-6 $M_{\odot}pc^{-2}$ and that of all <u>identified matter (stars and gas)</u> is 42+/-5 $M_{\odot}pc^{-2}$

- The local density of **dark matter** is 0.0075+/-0.0023 $M_{\odot}pc^{-3}$ (Zhang etal 2012) (see next lecture for how this is done)

Cosmic Rays-**105th** Anniversary of their Discovery

http://www.aps.org/publications/apsnews/201004/physicshistory.cfm

- These are very hard to study in other galaxies
  - they are visible by the synchrotron emission emitted by electrons spiraling in the magnetic field
  - γ-rays emitted by relativistic particles hitting gas producing pions which decay to γ-rays
- Milky Way

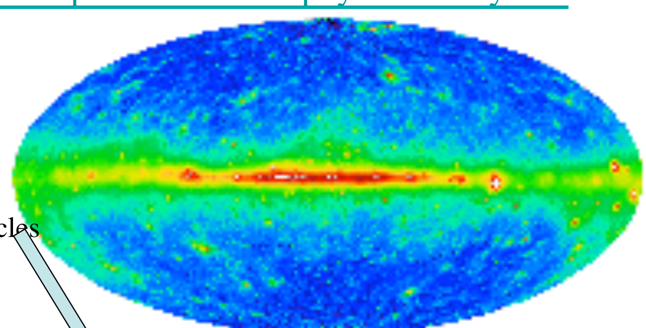
  direct measures of CRs e.g. in situ (S&G 2.4.1)

  detailed γ-ray maps of MW

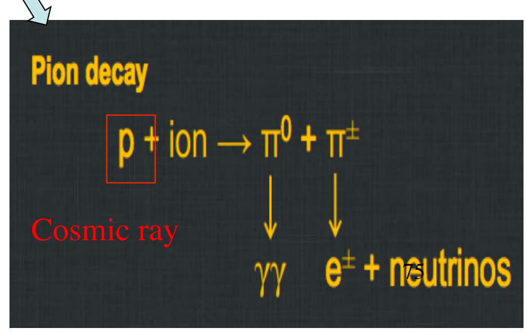
  convolution of cosmic ray energy spectrum and intensity with target (gas) density

  Very detailed radio maps

Origin: acceleration of particles in supernova shocks via first order Fermi process - total power ~10^{41} ergs/sec~10% of SN shock energy



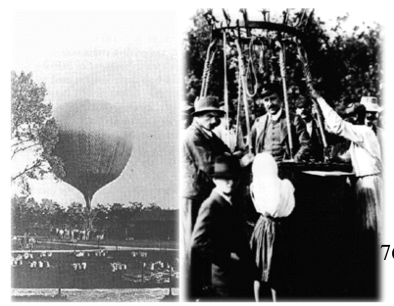
Fermi γ-ray map of MW



Cosmic Rays-105th Anniversary of their Discovery
Why Did Hess do This

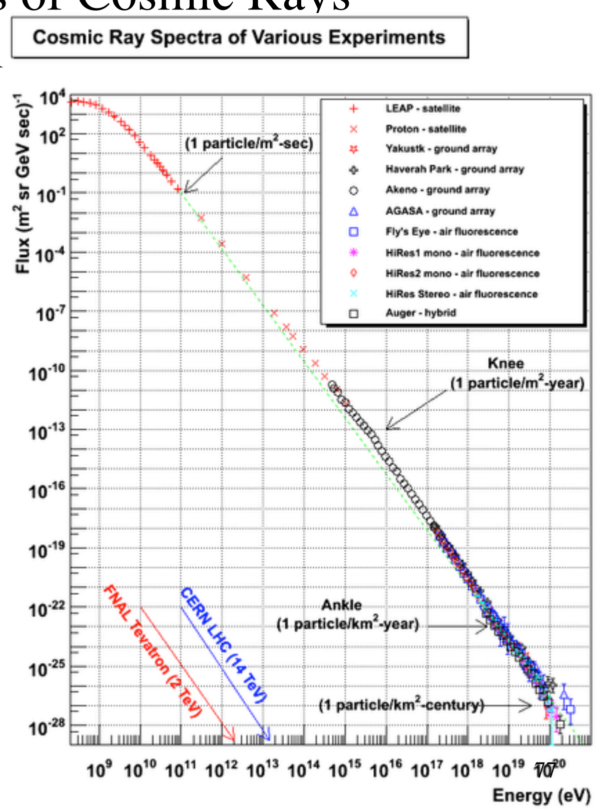
- scientists had been puzzled by the levels of ionizing radiation measured on the earth and in the atmosphere.
- The assumption was that the radiation from the earth and would decrease as one went away from the surface.
- Hess greatly increasing the precision of the electroscopes*and then by personally taking the equipment aloft in a balloon. He measured the radiation at altitudes up to 5.3 km during 1911-12 without oxygen. The daring flights were made both at day and during the night, at significant risk to himself and showed that the level of radiation increased as one went higher-observed during an eclipse and showed sun was not the origin.
- *He concluded that there was radiation coming from outer space ! (Nobel prize 1936)*

*they spontaneously discharge in the presence of ionizing radiation. The rate of discharge of an electroscope is then used as a measure of the level of radiation



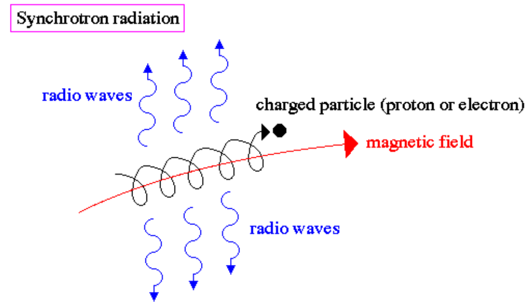
105 Years of Cosmic Rays

- Cosmic ray particle spectrum at Earth over 11 orders of magnitude in energy and 32 orders of magnitude in flux
- In August 1912, the Austrian physicist Victor Hess flew in a balloon to altitudes of 5.3 km, measuring the flux of particles in the sky. The expectation was that the flux would decrease with altitude, precisely the opposite of what Hess found. The shocking conclusion was that particles were raining down on Earth from space.
- http://www.npr.org/blogs/13.7/2012/07/25/157286520/cosmic-rays-100-years-of-mystery



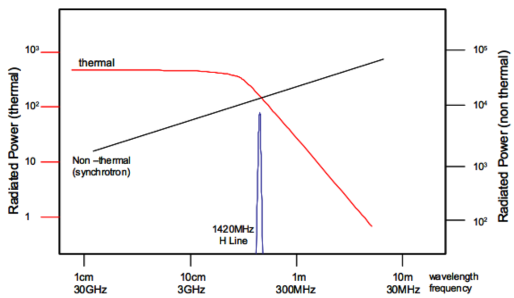
Cosmic Rays

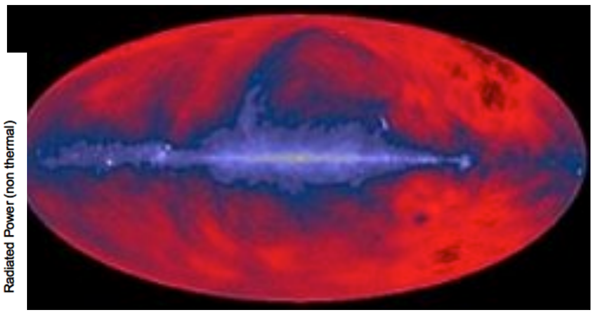
- Have appreciable energy density ~1 eV/cm^3
- Synchrotron emission is convolution of particle spectrum and magnetic field- also emission from 'non-thermal' bremmstrahlung
- Can ionize deeply into molecular clouds



http://abyss.uoregon.edu/~js/glossary/synchrotron_radiation.html

radio emission from galaxy





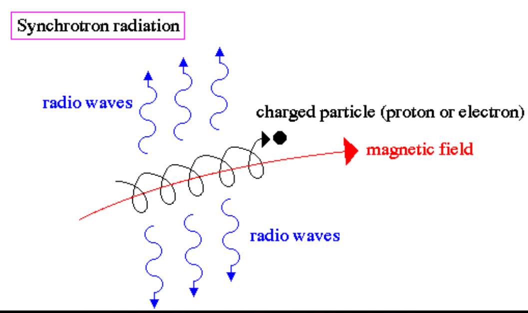
Intensity of radio continuum from MW

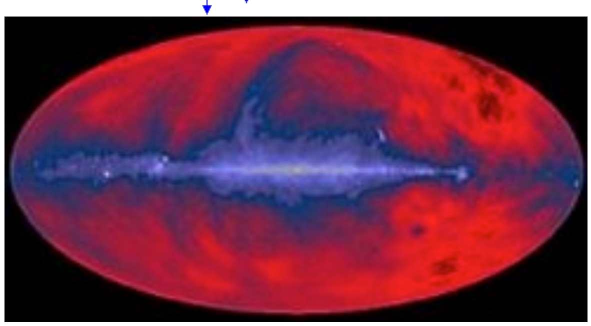
Radio Continuum Emission

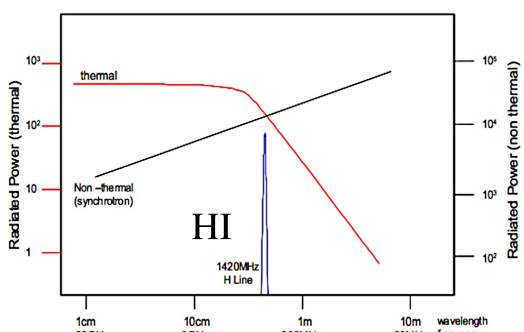
- Synchrotron emission: convolution of particle spectrum and magnetic field-power law spectrum- $F_\nu \sim A\nu^{-\alpha}$

slope, α depends on spectrum of CRs and flux also depends on intensity of magnetic field

- Thermal bremmstrahlung: fast, non-relativistic particles running by gas (breaking radiation)-exponential spectrum
- Relative intensity of the two components changes greatly with position.







radio continuum image of MW

Cosmic Rays

- Accelerated particles propagate through the Galaxy where, due to the magnetic field, they move along complicated helical tracks.
- Therefore, the direction from which a particle arrives at Earth cannot be identified with the direction to its source of origin (Larmor radius, r= $m_e c(\mathrm{sqrt}(\gamma^2-1)/eB$ (eq. 14.18 MBW) ; **3.3×10^6km~10^{-7} pc** for 1μG, 100Mev))
- The magnetic field is also the reason why particles do not leave the Milky Way along a straight path, but instead are stored for a long time (~ 10^7 yr) before they eventually diffuse out, an effect called confinement

γ-ray Imaging of Star Forming Regions

- Fermi has imaged the γ-rays coming from star forming regions and γ-ray spectra show that this is due to cosmic rays interacting with dense –
- Fermi has imaged sites of CR creation !

Fig. 1 Typical ~1pc Star Forming Region Shown by Bright O & B Stars

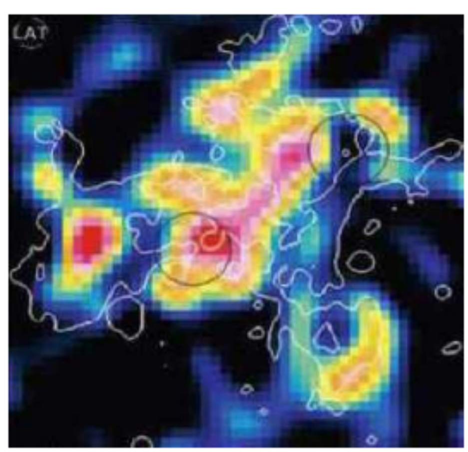


Fig. 2 ~100 pc Cygnus Superbubble in 10-100 Gev γ-Rays from Fermi [11]

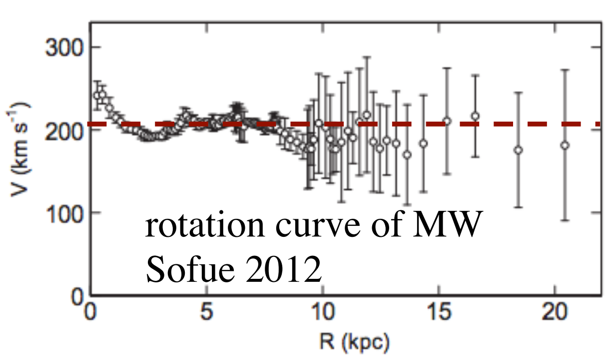
Simple Estimate of Mass of Milky Way

- ... follow problem S&G 2.18 and use $M \sim RV^2/G$- [of course this is for a sphere ... ignore the details (discuss later what is correct for a disk +sphere)]
- sun's distance from enter $R_0 \sim 8$kpc and rotational velocity ~220km/sec

  $M=9\times10^{10}\,M_\odot$ - corresponds to a density of $\sim 4\times10^{-3} M_\odot/pc^3$ (uniform sphere) - mass within 8kpc; if extend to 350kpc (virial radius) get $4\times10^{12}\,M_\odot$; factor of 2-4 too high but right 'order'
  - critical density of universe today $\rho_{crit}=3H_0^2/8\pi G \sim 1.45\times10^{-7}\,M_\odot/pc^3$ (from cosmology)
- So the MW is 'overdense' by $\sim 2.7\times10^5$ at solar circle and 600 at viral radius (using above simple formula) and 150 using a more correct mass.
  - In CDM theories the size of a virialized system is when the overdensity is >200

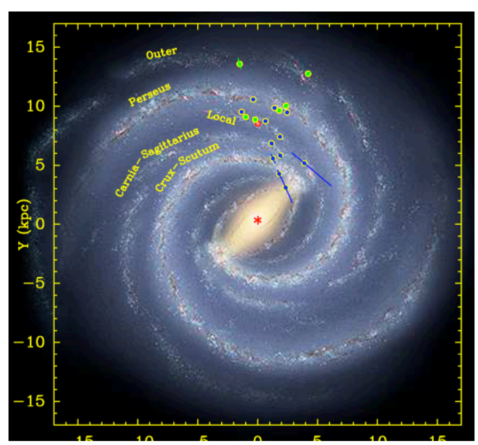
Mass of Milky Way

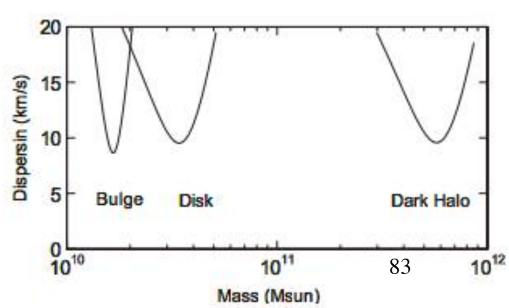
- Rather hard to determine- (the degeneracy between velocity and distance)- use rotation curve fitting and 'proper' potentials
  - absolute distance can be determined for several star forming regions (Reid et al 2009)
  - Partitioning the mass of the MW into bulge, disk and DM halo
-



rotation curve of MW
Sofue 2012

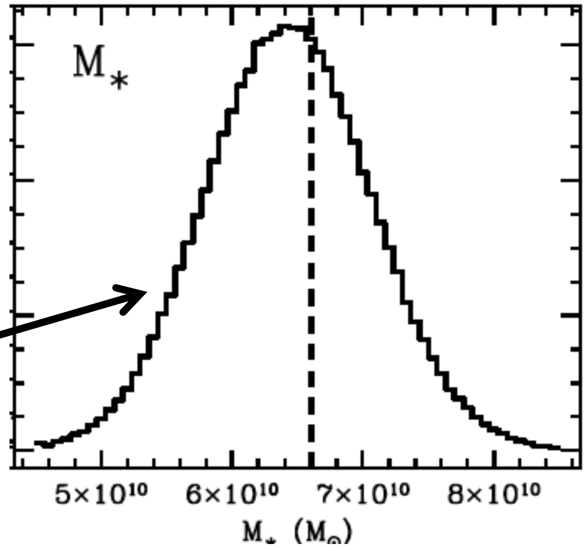
Locations of star-forming regions (dots) artist's Milky Way.





Mass of Milky Way

- The majority of the mass of the Galaxy is in the CDM halo-only observable through its gravitational effect on luminous components of the Galaxy
  - at sun thin disk has 90% of the mass and thick disk 10%
- total stellar mass of $6.43 \pm 0.63 \times 10^{10} M_\odot$
  - bulge mass $M_b = 8.9\ 10^9\ M_\odot$
- Virial mass of $1.26 \pm 0.24 \times 10^{12} M_\odot$
- Ratio of dark matter to baryons is ~20:1- galaxy is baryon poor with respect to the average for the universe.



Probability distribution of M_{star}
McMillian 2012

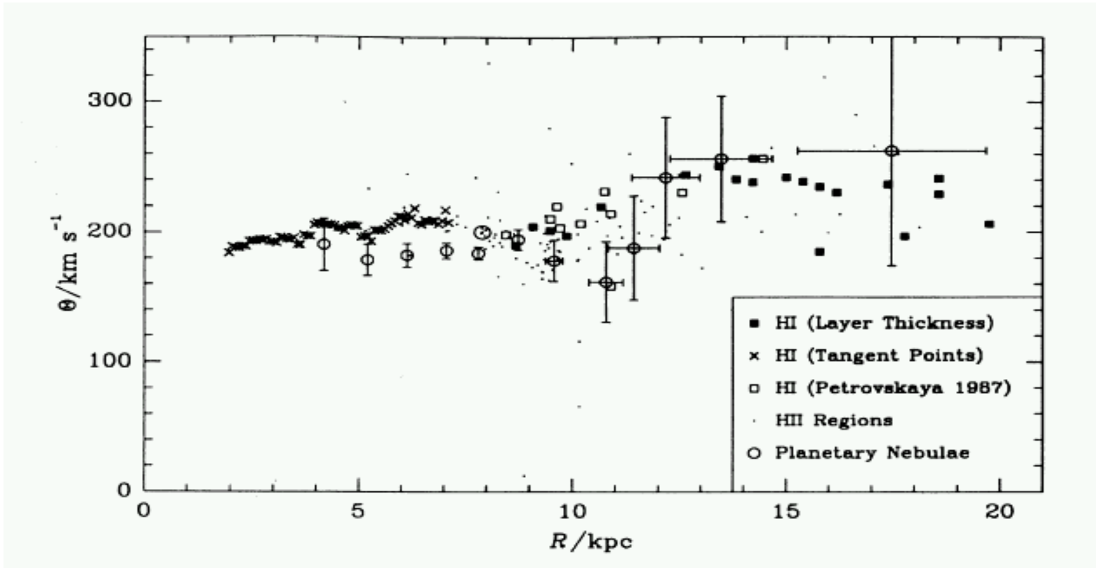
a local dark matter density of 0.40 ± 0.04GeVcm^{-3} (or in more normal units $0.01\ M_\odot/pc^3$)

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

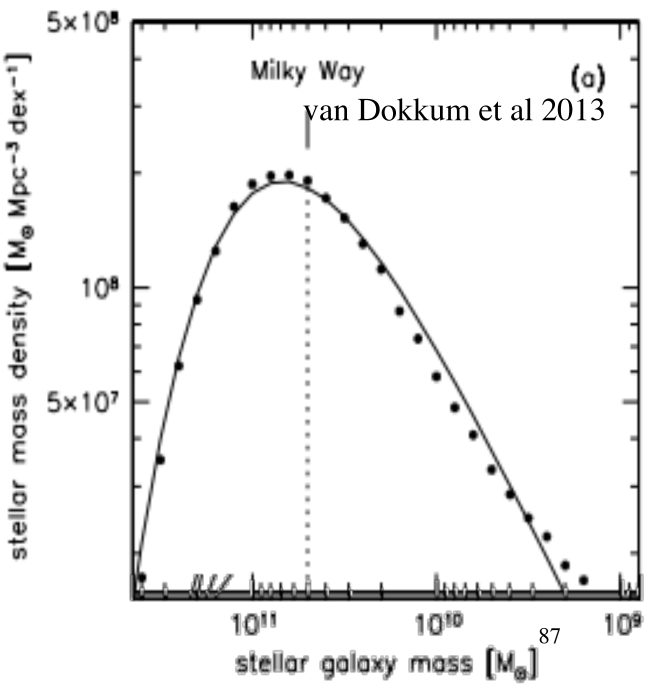
MW Rotation Curve



- Flynn, Sommer-Larsen , Christensen 1996

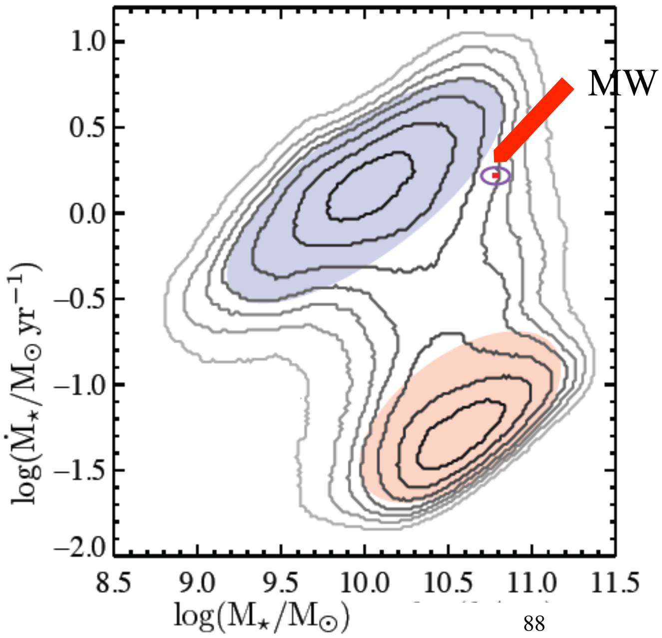
Stellar Mass of MW compared to Local Galaxy Mass Function

- 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)



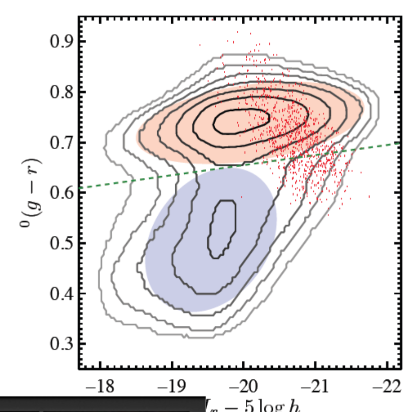
The MW as Representative of Other Galaxies

- 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, can remove effects of dust by using other galaxies.



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)



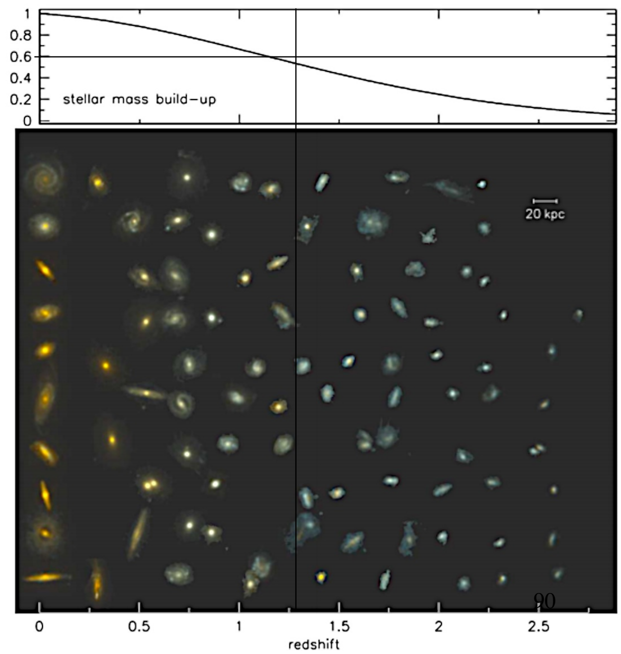
Progenitors of the MW

- 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

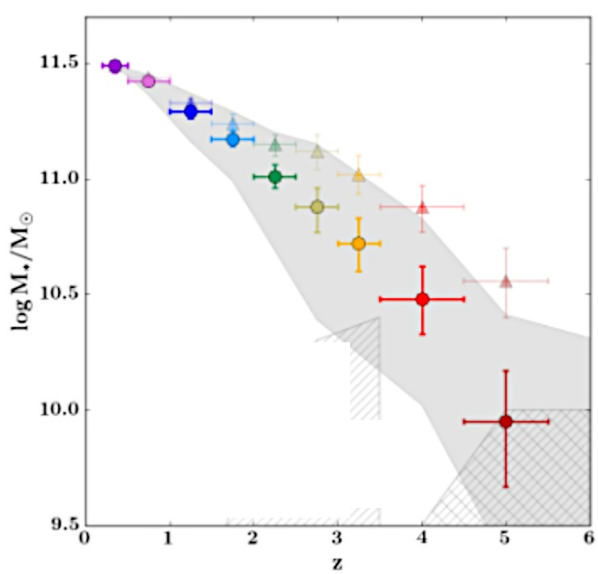
- at higher redshift galaxies had a very different shape

- Galaxies also become redder with time (general drop of SF at low redshift)



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).



"The Formation and Evolution of the Milky Way," by Cristina Chiappini; 2001

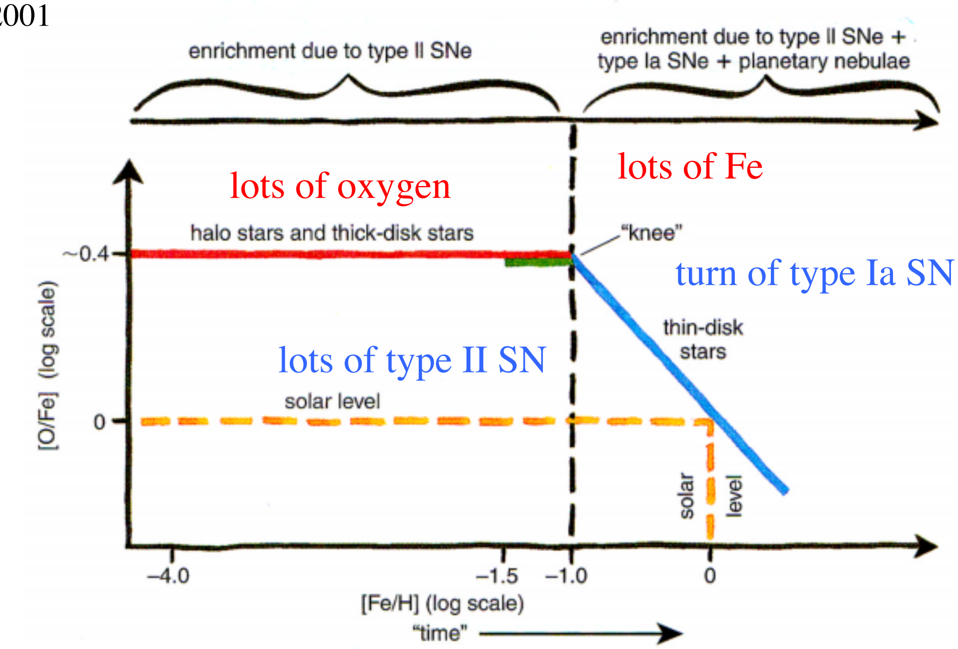


Figure 5. The general metallicity of the Galaxy—as measured by the abundance of iron (Fe), compared with hydrogen (H)—increases with time *(abscissa)* and so serves as a basis for comparing the relative abundances of two elements (such as oxygen (O) and iron; *ordinate*) that are created on different timescales. A plot of these quantities reveals a "plateau" of metal-poor stars (metallicity less than -1) that drops at a "knee" as the relative proportion of iron in the Galaxy increases. Since type Ia supernovae (SNe) are the primary source of iron, astronomers believe that the "knee" occurred about one billion years after the Galaxy began to form *(see Figure 4)*. The halo stars *(red line)* and some of the thick-disk stars *(green line)* tend to occupy the "plateau," whereas thin-disk stars *(blue line)* occupy the descending slope. These observations suggest that the halo, and part of the thick disk were formed in the first billion years of the Galaxy's evolution, and the think disk formed later.

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
- 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;

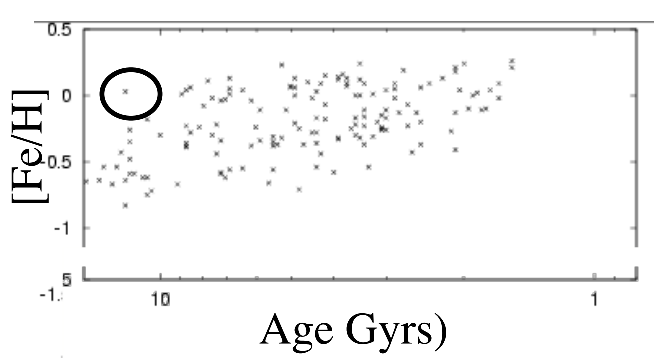
–galaxy is not a closed box, gas flows in and out

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

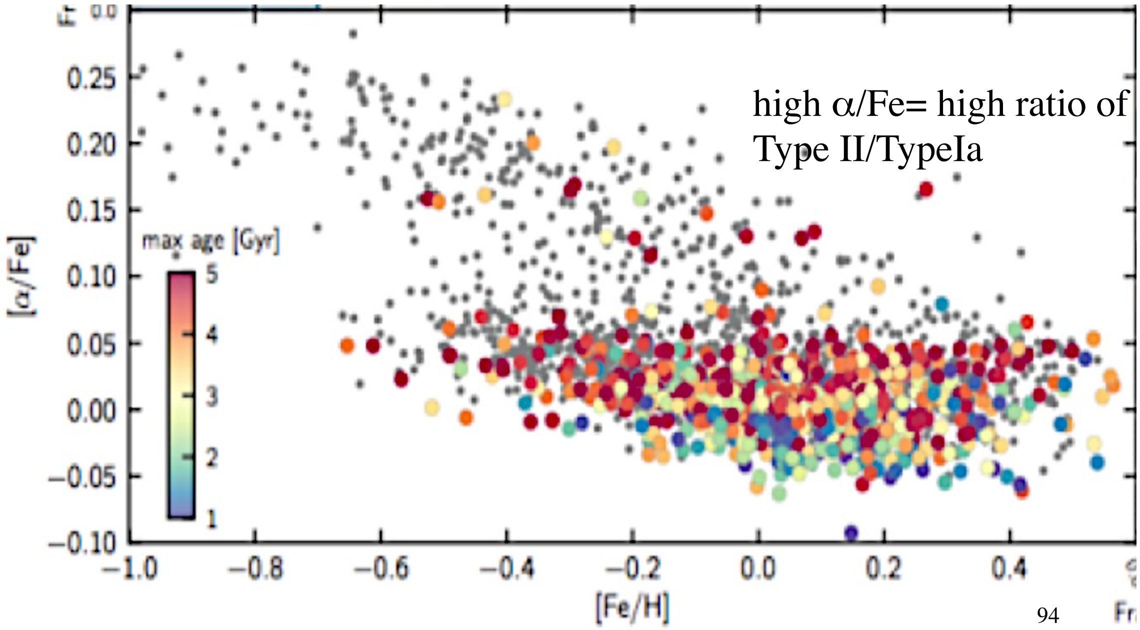
–star formation rate is not constant



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

Relationship of Metallicity, Composition and Age

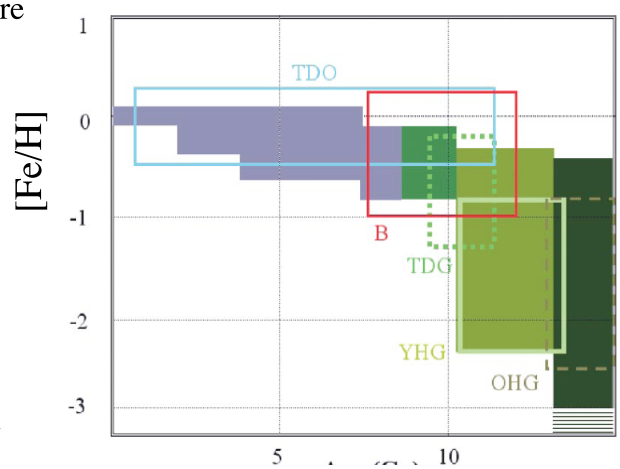
- New data (2016) situation is very complex... general trend to old stars to have high α/Fe (APOGEE results)



Components of MW Disk

- The positions, velocities, chemical abundances, and ages of MW stars are very strongly and systematically correlated
  - For example in the disk:
    - younger and/or more metal-rich stars tend to be on more nearly circular orbits with lower velocity dispersions.
- Subcomponents of the Disk can be defined on the basis of the spatial distribution, kinematics, or chemical abundances.
- Most common has been to describe the Disk in terms of a dominant thin disk and a thick disk, with thin–thick disk samples of stars defined spatially, kinematically, or chemically

Freeman and Bland-Hawthorn



AGE (Gyrs)

blue= thin disk stars

green =thick disk stars

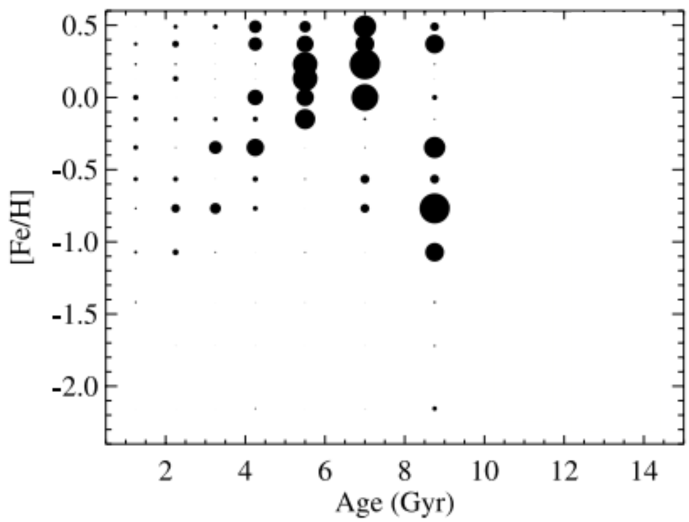
B= bulge stars

black= halo stars

Age Metallicity

- Now can do this in M31 with HST data (!)
- Pattern seems to be more variance at younger ages, rather than a trend.
- In M31 spheroid things are very different than in MW; 40% of the stars are metal-rich and younger than 10 Gyr ! (M31 has undergone a major merger MW has not)

- Lesson: MW may not be representative of all spirals



Size of symbol is ~ # of stars in box; Brown et al 2006

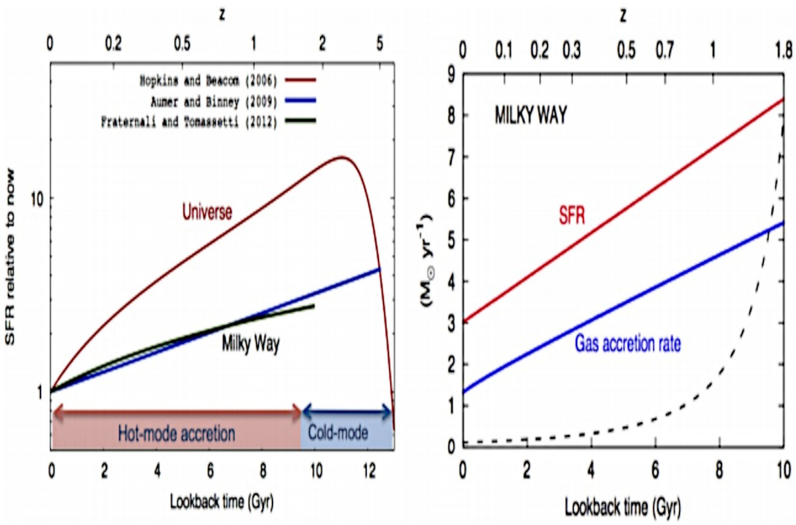
Populations, Chemistry and Dynamics

- The formation of the stellar population of a galaxy is a complex process.
  - Star formation takes place in dense regions, forming stellar clusters that sooner or later are disrupted due to the tidal stripping and internal evolution. When they dissolve they leave imprints in velocity space.
  - the orbits of the stars in the disk are perturbed by non-axisymetric effects (e.g. spiral arms and the bar), making stars migrate from where they were born
  - merging satellites produce dynamical streams leaving stars behind in the disk

- All this severely complicates the simple idea of metallicity and age being easily connected.

MW as Model for Other Galaxies

- the Milky Way experienced very few minor mergers and no major merger during the last ~10Gyrs- unexpected in a cosmological scenario
- The old stellar content of the thick disk indicates a possible a merger origin at an early epoch.
- The Milky Way is presently absorbing the Sagittarius dwarf though this is a very tiny event (<1% of the Milky Way mass)



SF history of MW (Fraternali 2013) MW SFR does not match that of the universe as a whole (but it shouldn't- at high z elliptical galaxies dominate)

Onward to Detailed Dynamics

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

Local Standard of Rest

The Sun (and most stars) are on slightly perturbed orbits that resemble rosettes making it difficult to measure relative motions of stars around the Sun.

Establish a reference frame that is a perfect circular orbit about the Galactic Center.

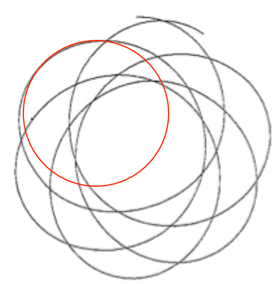
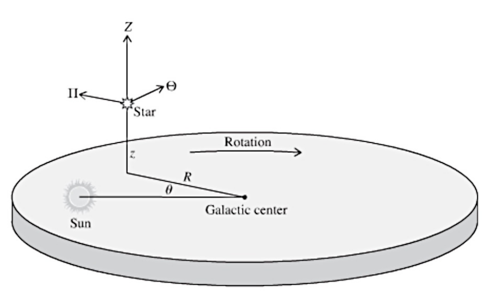


Figure 3-1. A typical orbit in a spherical potential forms a rosette.

Local Standard of Rest - reference frame for measuring velocities in the Galaxy.
Position of the Sun if its motion were completely governed by circular motion around the Galaxy.

Use cylindrical coordinates for the Galactic plane to define the Sun's motion w.r.t the Local Standard of Rest



Galactic Rotation

- Then using a bit of trig

$R(\cos\alpha) = R_0\sin(l)$

$R(\sin\alpha) = R_0\cos(l) - d$

so

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

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

then following the text expand $(\omega - \omega_0)$ 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

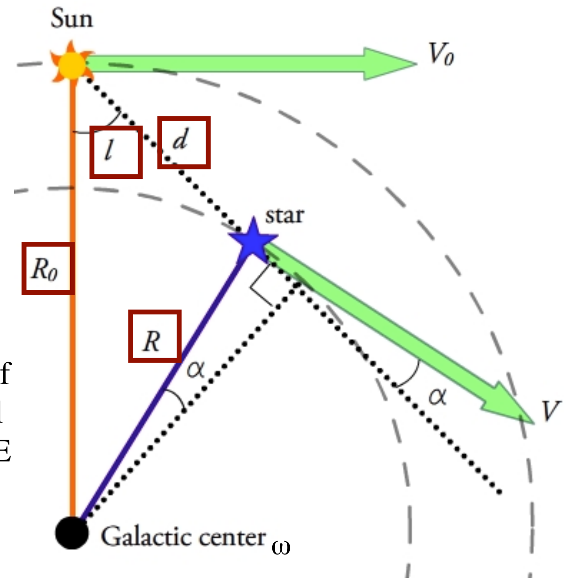
get

$V_{observered,radial} = Ad\sin(2l); V_{obs,tang} = Ad\cos(2l) + Bd$

Where

$A = -1/2\ R_0 d\omega/dr$ at R_0

$B = -1/2\ [(R_0 d\omega/dr) - \omega]$



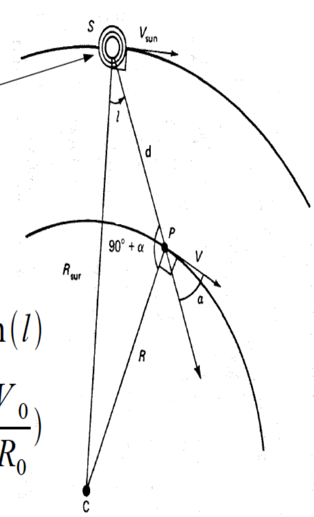
Galactic Rotation Curve- sec 2.3.1 S+G

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)

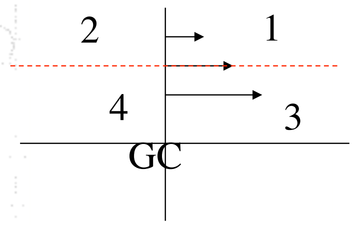
- Galactic Rotation Curve
  - At R_{sun} the lsr has a velocity of V_0
  - A star at P has an apparent velocity of

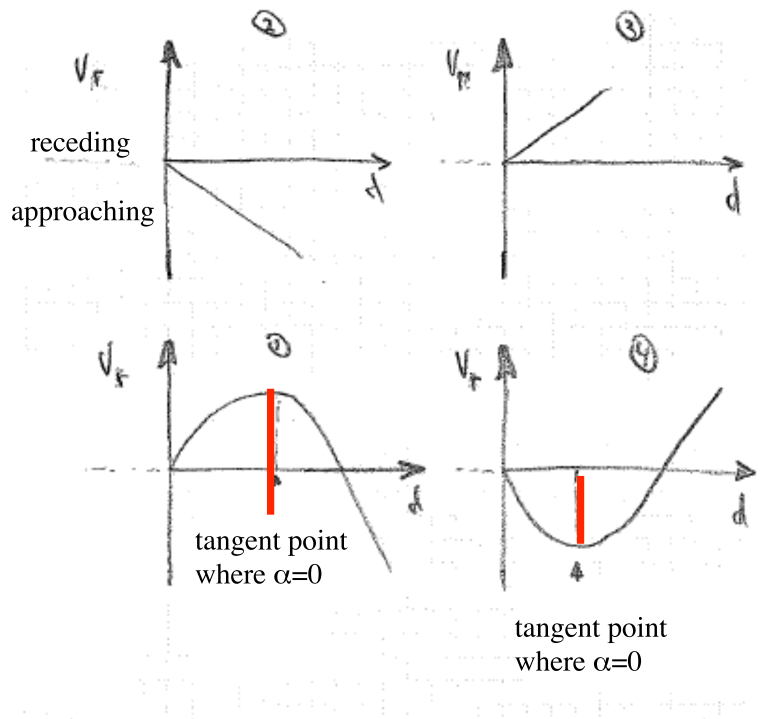


1) $V_r = V\cos(\alpha) - V_0\sin(l)$

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

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





(1) $0<l<90$

(2) $90<l<180$

(3) $180<l<270$

(4) $270<l<360$

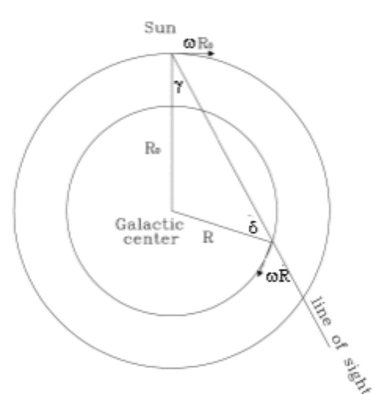
Veilleux 2010

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 ω 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 γ)
- ω = angular velocity at distance R

  ω_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

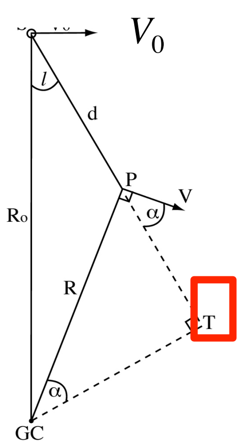
- The tangential velocity $v_T = V\sin\alpha - V_o\cos l$ and $R\sin\alpha = R_o\cos l - d$
- a little algebra then gives

  $V_T = V/R(R_o\cos l - d) - V_o\cos l$
- 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 $0 < l < 90^\circ$, 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;

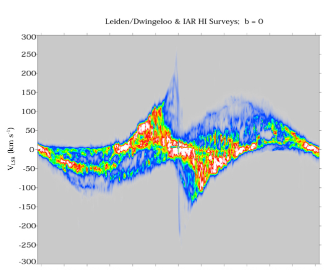
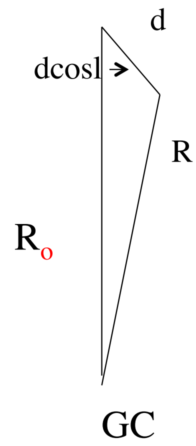


Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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 $d<<R_o$

$R-R_o=d\cos l$ 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)
  - $V(R)\sim R_0\sin l\,(d(V/R)/dr)(R-R_0)$ $\sim d\sin(2l)[-R/2(d(V/R)/dr)\sim dA\sin(2l)$
- 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

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

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

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

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

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 $AR_0\sim 115\text{km}/_s$

Oort 'B'

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

  $\boldsymbol{\omega=A-B=V_0/R_0}$; 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

  Values

  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

Future Problems for Analytic Methods for Detailed Mass Measurements

- Tidal stripping of dark matter from subhalos falling into the Milky Way produces narrow, "cold" tidal streams as well as more spatially extended “debris flows” in the form of shells, sheets, and plumes.

- The matter in the solar neighborhood is commonly assumed to be smoothly distributed in space and to have a Maxwellian velocity distribution- but....

- Tidal effects tend to make the density distribution smooth, but these tidal disruption processes are sources of **velocity substructure**.
- the speed distributions measured in high resolution numerical simulations exhibit deviations from the standard Maxwellian assumption, especially at large speeds.

Kuhlen et al 2012