Measuring Structure of the Galaxy

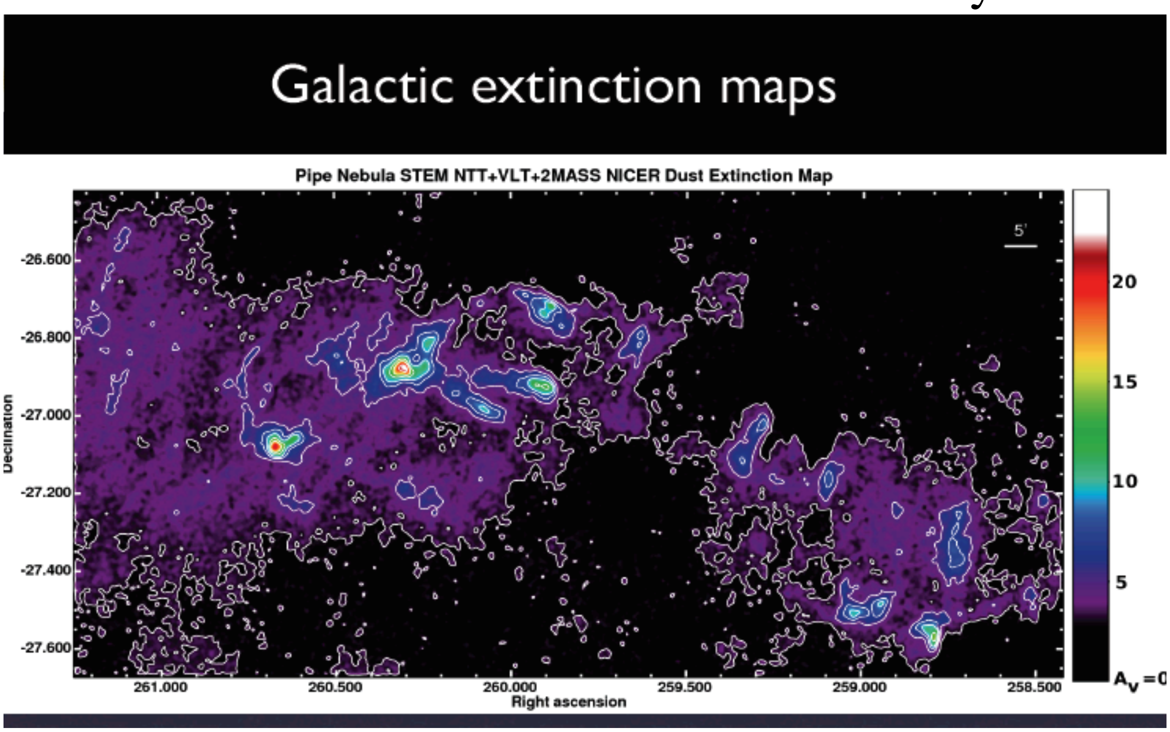
- To invert the measured distribution of stars
  - A(m,l,b): # of stars at an **apparent mag m**, at galactic coordinates l,b per sq degree per unit mag.
  - N(m,l,b): cumulative # of stars with mag **< m**, at galactic coordinates l,b per sq degree per unit mag.

$$N(m,l,b)=\int A(m',l,b)\, dm$$

Into a true 3-D structure

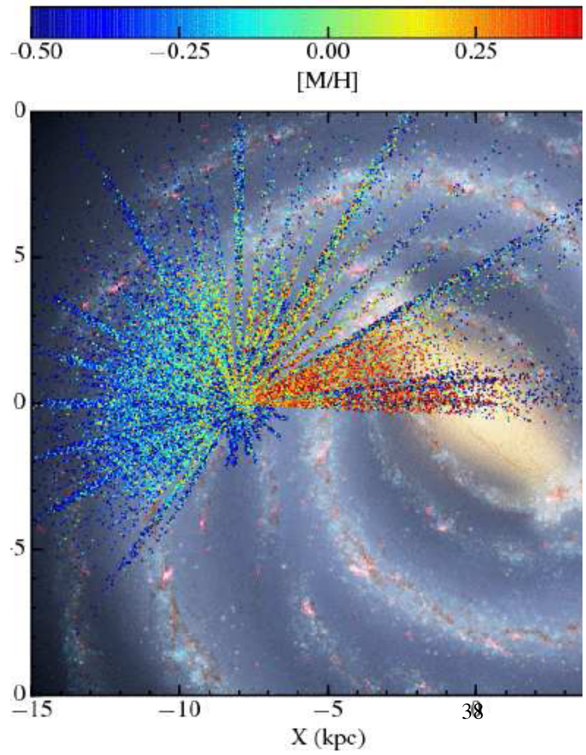
One needs to make a lot of 'corrections' the biggest one is due to extinction so one does not repeat Herschel's error!

Need to Measure Extinction Accurately



APOGEE Results

- Metallicity across the Milky Way
- An example of the fine grain knowledge now being obtained.

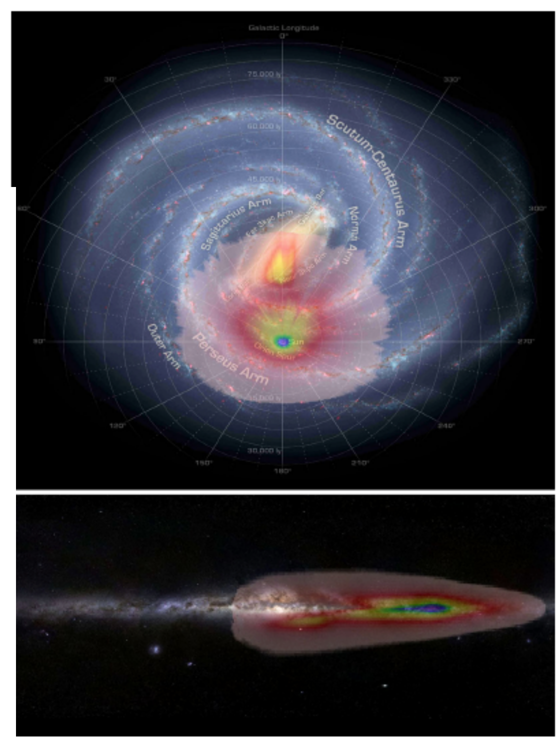


Gaia Capability

- Gaia will survey ~1/4 of the MW (Luri and Robin)

able 2 Stellar spectroscopy surveys of the Milky Way

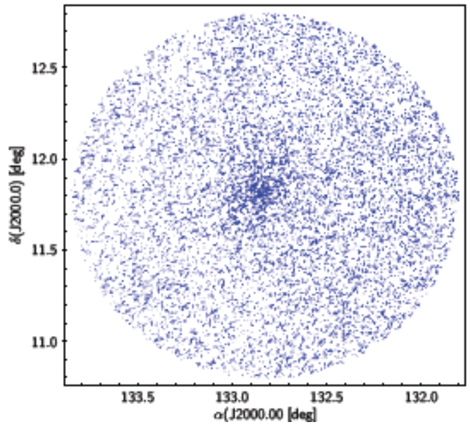
urvey	Period	Sky Area	# of Spectra	app. mags	δv [km/s]	δ[Fe/H]	char. distance
CS	1981–2000	South	16,000	$V \simeq 10?$	0.5	indiv	0.003 kpc
EGUE I + II	2004–2009	North, $l > 20°$	360,000	$g = 15–20$	8	0.2	2 kpc
AVE	2003–2012	South	370,000+	$i = 9–12$	3	0.2	0.5 kpc
POGEE	2011–2014	North, $l < 20°$	100,000	$H < 13.8$	0.5	indiv.	10 kpc
aia-ESO	2012–2015	South	150,000	$V < 18$	0.5	indiv.	4 kpc
AMOST	2012–2018	North	3,000,000	$V < 18$	10	0.2	4 kpc
a	2013–2018	all sky	50,000,000	$V < 16$	10	0.25	4 kpc

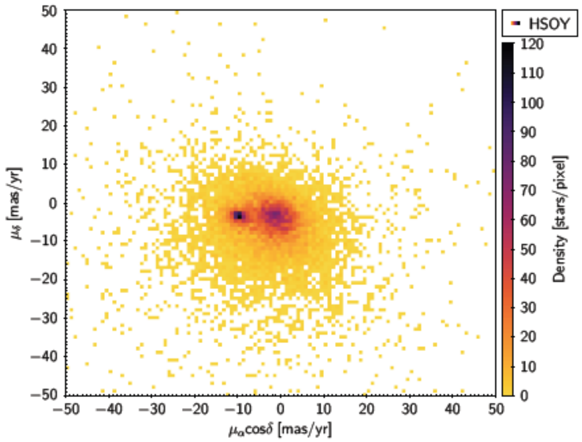


l A view of our Galaxy and the effective volume that Gaia will survey (courtesy X. Luri a
bin), based on current simulations of Gaia mock catalogs. Even in the age of Gaia, dust extincti
nage crowding will limit the exploration of the Disk to only a quadrant with optical surveys

Early GAIA Results

- Proper motions in the M67 star cluster-accuracies of ~5mas/year ($5x10^{-9}$ radians/year or $4.3x10^{-5}$ pc/year (42 km/sec- 2.5x the speed of the earth around the sun) at distance of M67)





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

Timescales

- crossing time t_c=2R/σ~5x10^{7}yrs (R_{10kpc}/v_{200})

- dynamical time t_d=sqrt(3π/16Gρ)- related to the orbital time; assumption homogenous sphere of density ρ

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

S+G (eq. 3.55) gives

$$\mathbf{t_r=V^3/8\pi G^2 m^2 n \ln\Lambda}$$

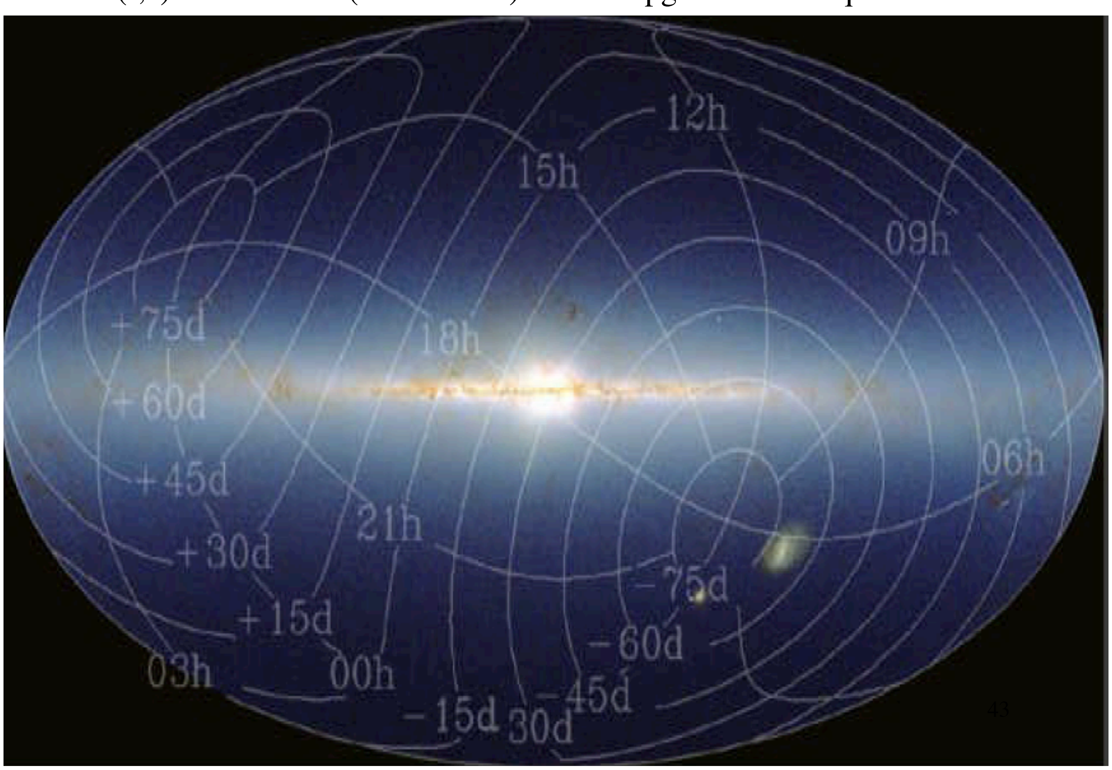
$$\mathbf{\sim 2x10^9 yrs/[(V/10km/sec)^3(m/M_\odot)^{-2}(n/10^3pc^{-3})^{-1}}$$

major uncertain is in lnΛ− numerical simulations ~20

m-mass of stars, n= number density of stars

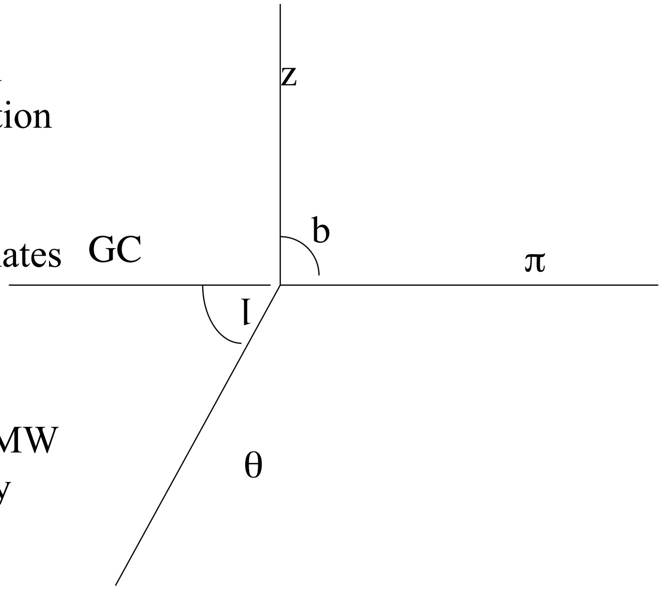
Coordinate Systems

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



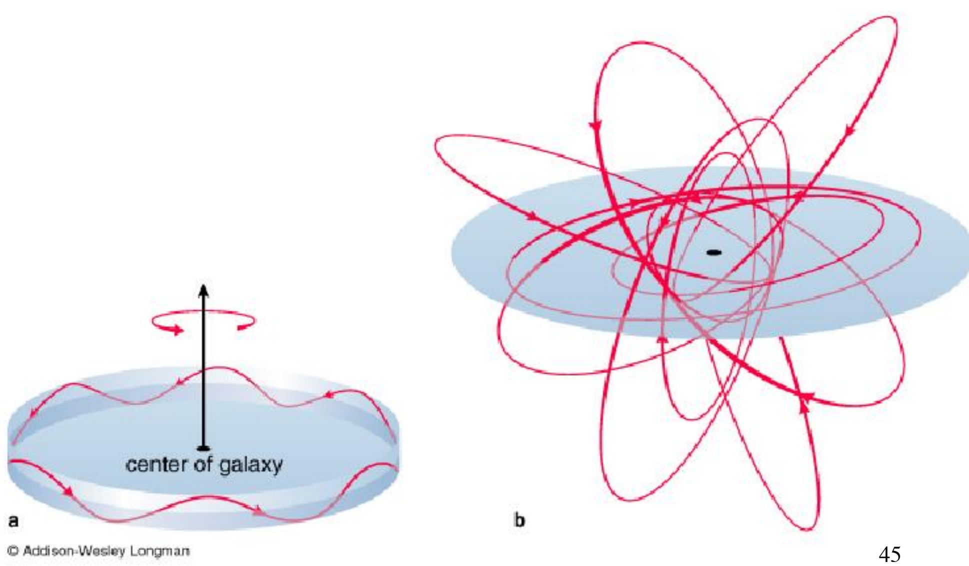
Coordinate Systems

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
(π,θ,z)LSR=(0,θ_0,0);



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



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.

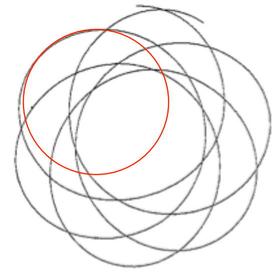
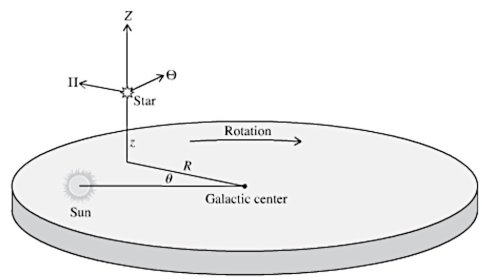


Figure 3-1. A typical orbit in a spherical potential forms a rosette.

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



Motion of Stars

- Stars closer to the Galactic center complete their orbits in less time than do those further out.
- Inward, stars pass "us" in their orbits; their motion relative to us is in the same direction as the Sun's orbital velocity V_0. Outward, stars are "falling behind us", and thus have proper motions in the opposite direction .
- Stars at the same Galactocentric radius orbit at the same rate as the Sun, so they maintain a fixed distance and have a 'sideways' motion.
- For stars close to the Sun, the proper motion μ has a component that varies with Galactic longitude l as $\mu \propto \cos(2l)$

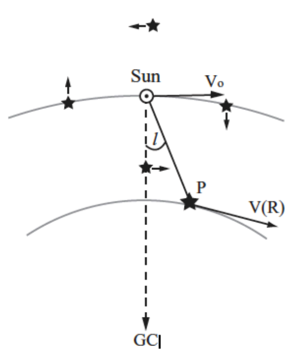


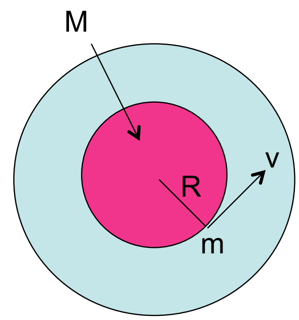
Fig. 2.18. Galactic rotation: stars closer to the Galactic center (GC) pull ahead of us in their orbits, while those further out are left behind. A star at the same Galactocentric radius moves sideways relative to us.

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.

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

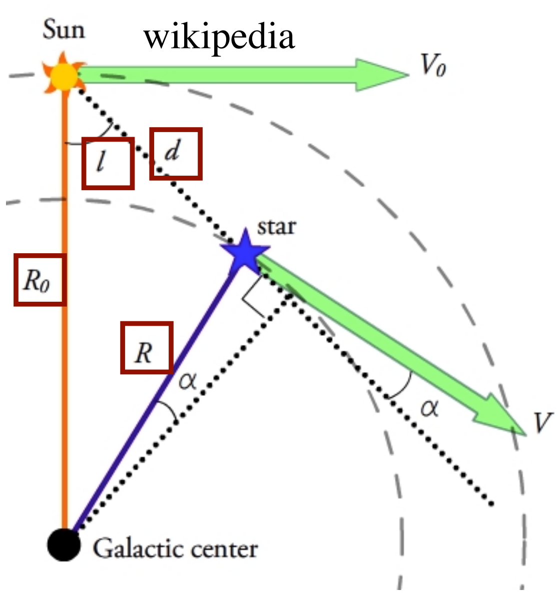
- Consider a star in the midplane of the Galactic disk with Galactic longitude, ℓ, at a distance d, from the Sun. Assume circular orbits radii of R and R_0 from the galactic center and rotational velocities of V and , V_0
- The 2 components of velocity- radial and trangential are for circular motion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

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

which gives

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

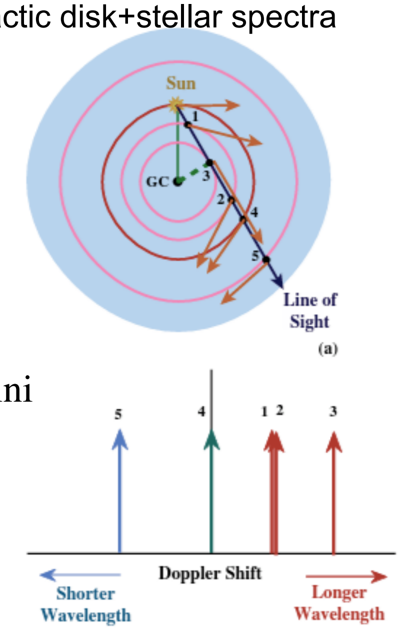
Much more later



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

Differential Rotation

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

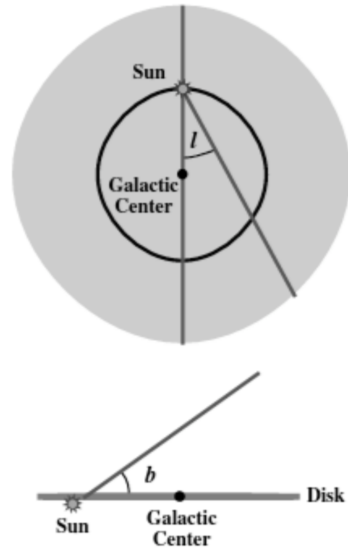


Sarajadini

Define Galactic Coordinates

b = galactic latitude in degrees above/ below Galactic disk

l = galactic longitude in degrees from Galactic Center

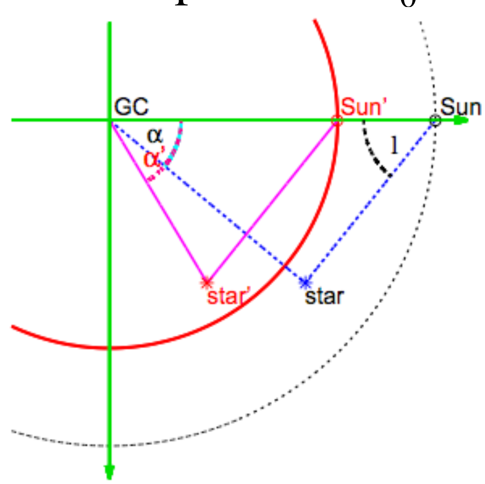


Why Rotation Curves for MW Depend on R_0

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

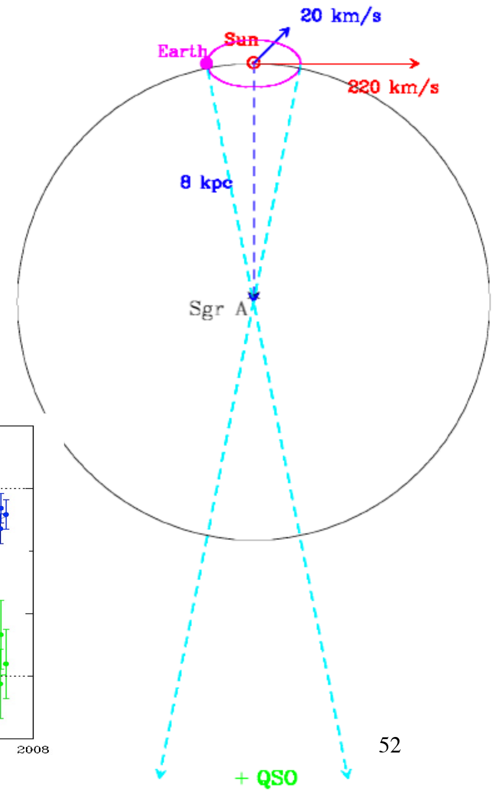
R. Schonrich

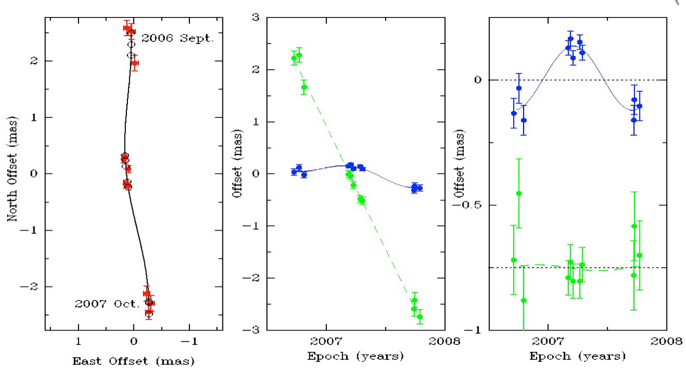


R_0= distance of sun from galactic cente

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 – possible with VLBI (Reid et al 2008)



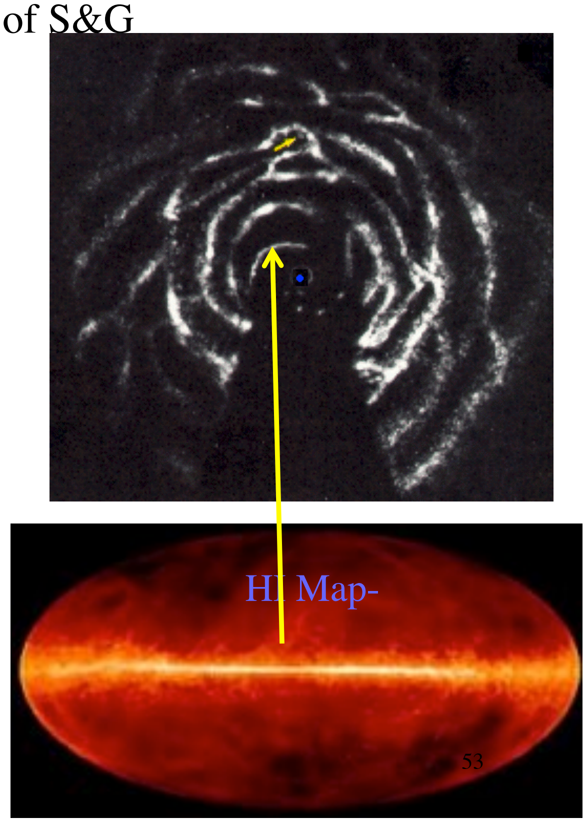


HI Maps- Major Way to Trace MW Velocity Field
Sec 2.3 of S&G

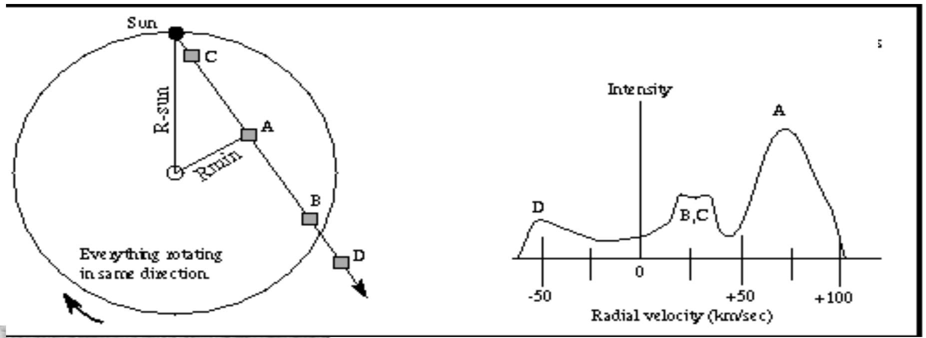
- HI lies primarily in the galactic plane- maps have velocity data associated with them- allows dynamics to be determined
  - deproject HI velocity and intensity map to show total structure of the galaxy
- Not affected by dust- shows detailed structures.

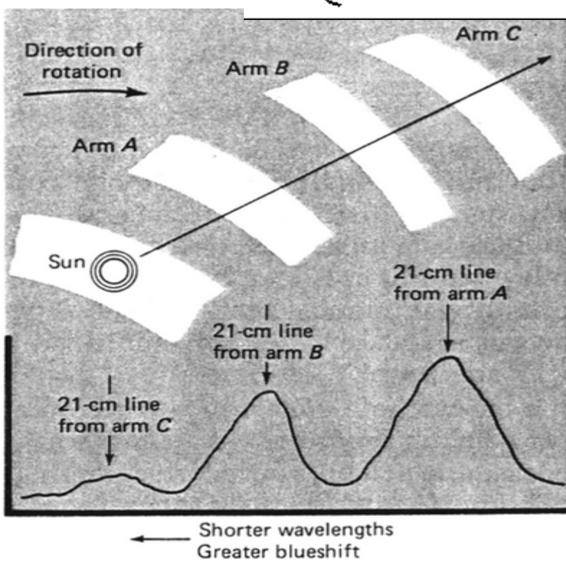
Neutral atomic hydrogen (HI) traces the interstellar medium (ISM) over a broad range of physical conditions.

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



Using HI





A has largest <u>angular speed</u>, is moving fastest away from sun and has higher line of sight mass of HI
B&C about same angular speed (> suns)
D is slower angular speed

Observed <u>radial velocity</u> of the cloud will be the difference between the Suns component of MW Rotation and the cloud along the line of sight
$V_r = V\cos\alpha - V_{sun} \sin l$

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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)

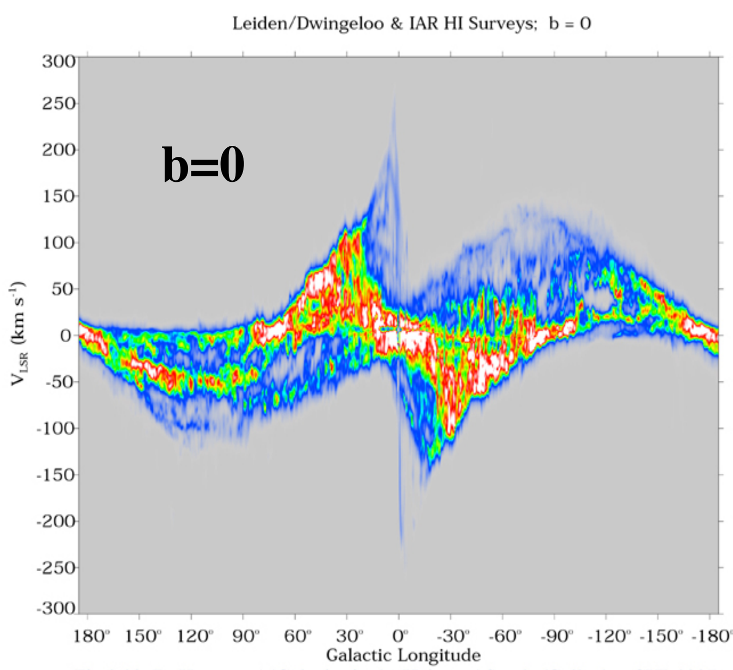

Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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

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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)

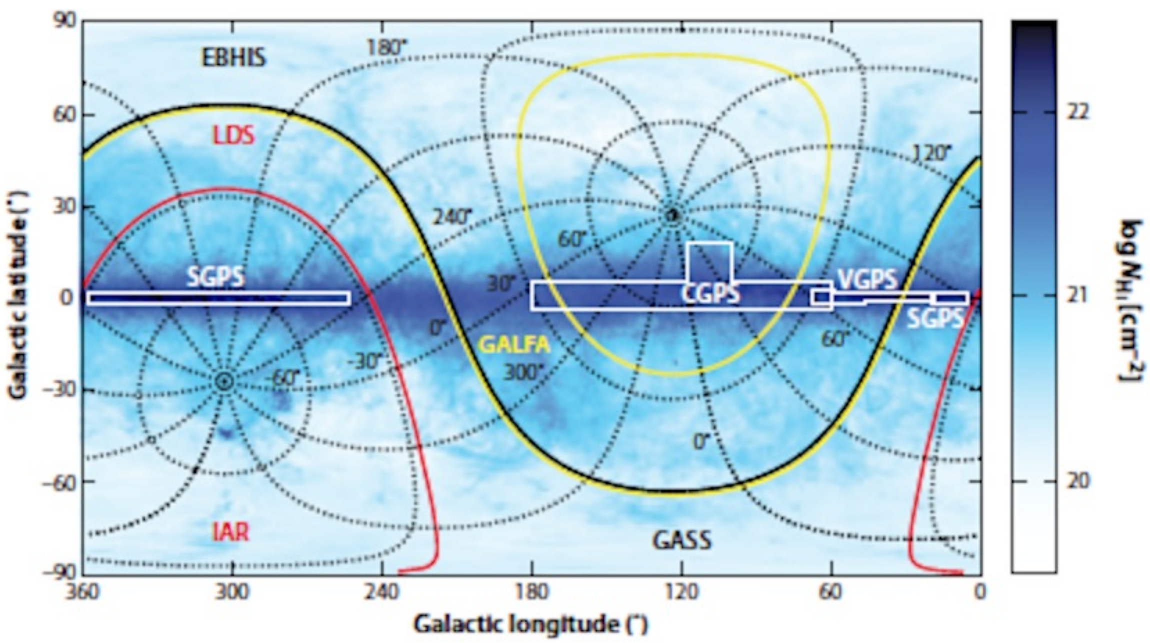
  $v(R, z)=[(R_{\odot}/R)\ \Theta(R, z)-\Theta_{\odot}]\sin(\ell)$ x $\cos(b)$ where v is the radial velocity along a line of sight (directly measurable); and Θ is the tangential velocity

- $V_r = R_0 \sin l[V/R - V_0/R_0]$; 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)

HI Intensity Map

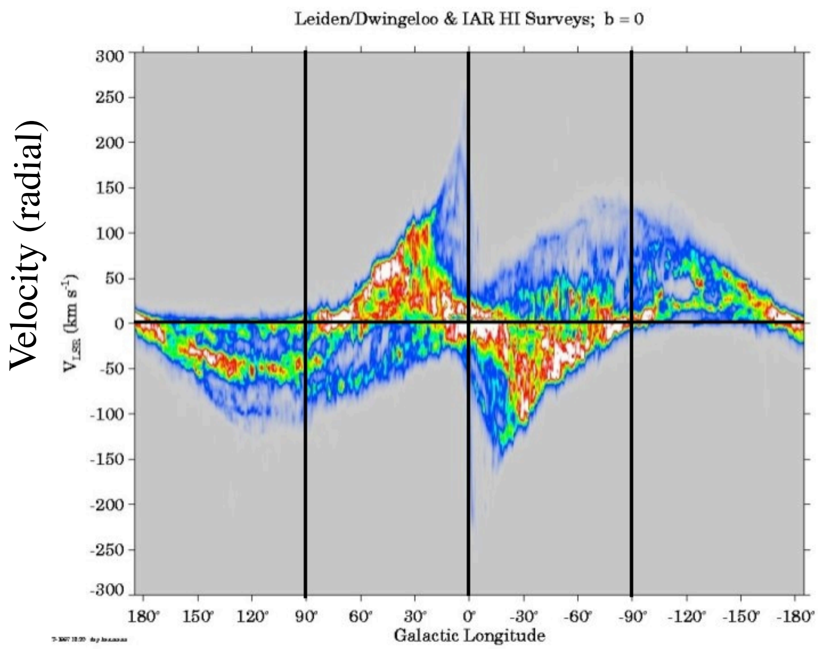


- Acronyms are the names of different surveys
- Dotted lines are ra and dec coordinates

Galactic Rotation Curve HI data

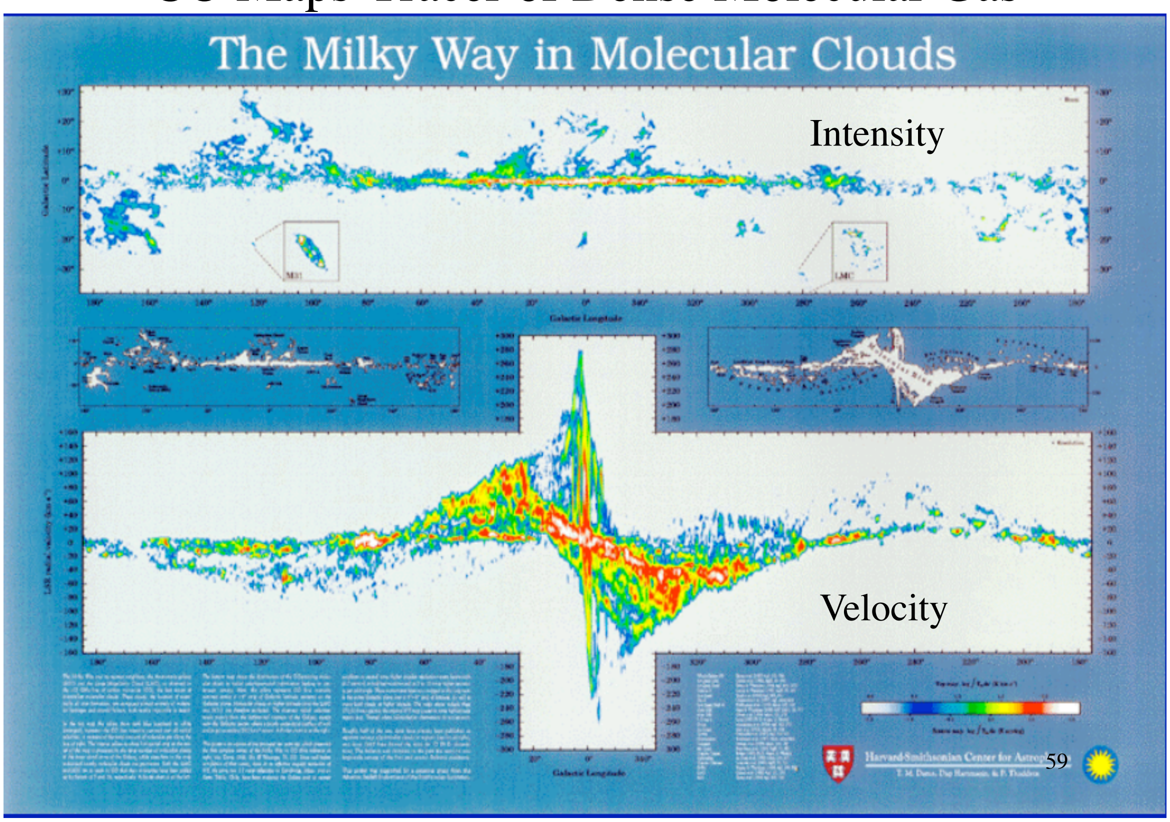
- Velocity, longitude, intensity graph of HI in the MW fig 2.20 in S+G
- The HI probes very large scales and **so many of the approximations in the derivation of the Oort constants are not adequate- see later.**

(S+G pg 92-93)



Galactic Longitude

CO Maps-Tracer of Dense Molecular Gas



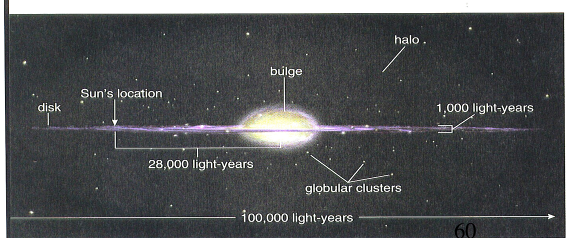
Basic Properties of MW

Diameter ~23Kpc (ill defined)
at sun orbital period ~$2.5x10^8$ yrs
Mass ~$2x10^{11}$ $M_{\odot}$ (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)~exp(-z/h); h=scale height
The disk is NOT simple and has at least 2 components

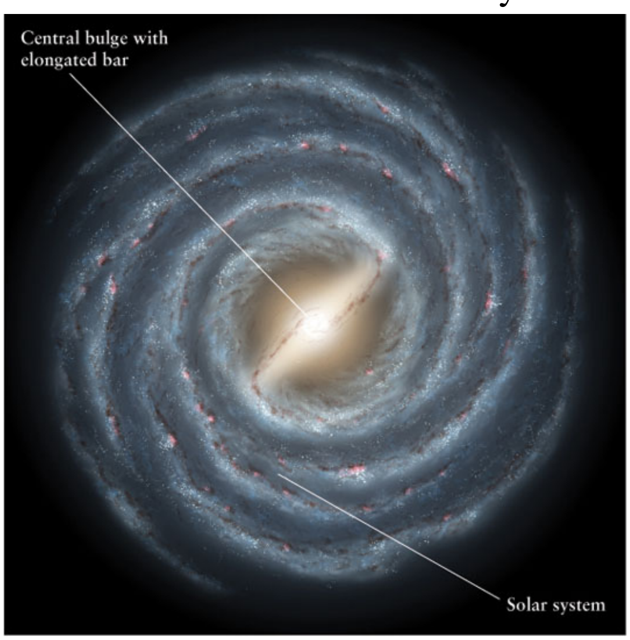
1) thin disk - largest fraction of gas and dust in the Galaxy, and star formation is taking place ; h~100pc, σ_z~20km/sec
2) thick disk h~1.5 kpc older, lower metallcity population, less gas- only makes up 2% of mass density **at z~0**.

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

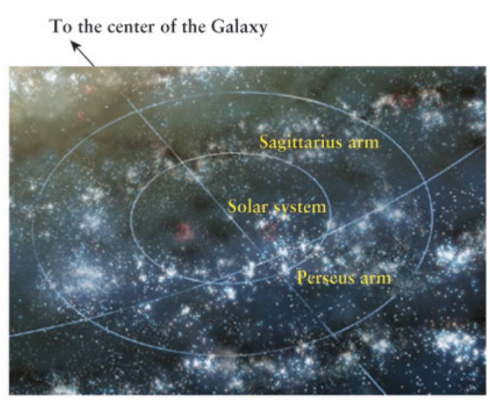


b Edge-on schematic view of the Milky Way.

MW is a Barred Galaxy



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



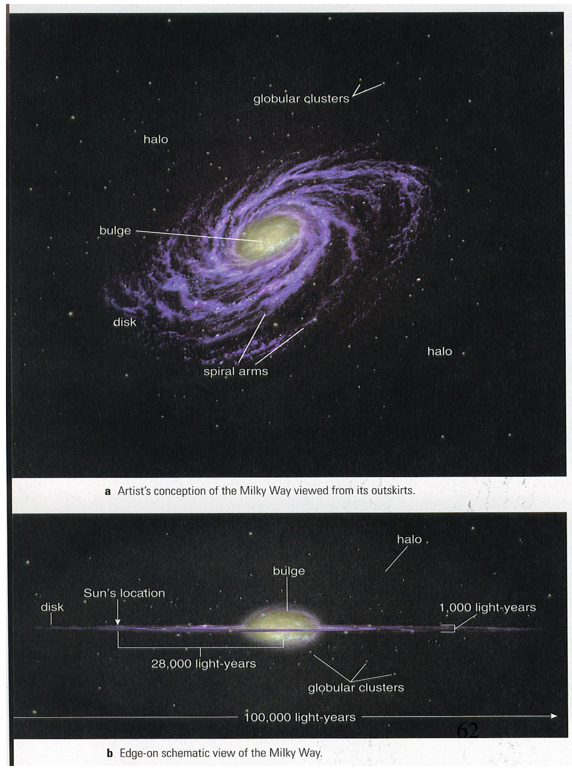
(b) Closeup of the Sun's galactic neighborhood

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

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: ~$5\times10^{10}\,M_\odot$
HI mass: ~$3\times10^9 M_\odot$
H_2 mass (inferred from CO mass):~$0.8\times10^9 M_\odot$

Total MW mass within viral radius is ~$8\times10^{11}M_\odot$: 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.

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

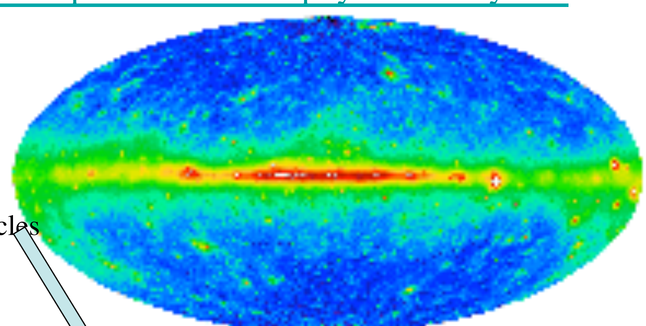
  direct measures of CRs e.g. in situ (S&G 2.4.1)

  detailed γ-ray maps of MW

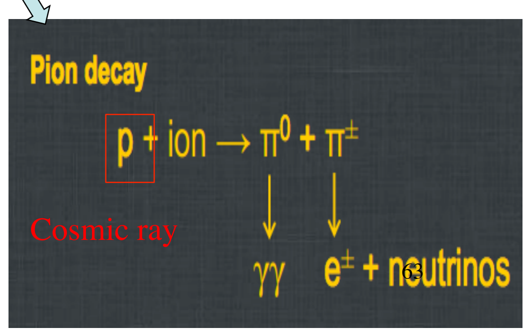
  convolution of cosmic ray energy spectrum and intensity with target (gas) density

  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

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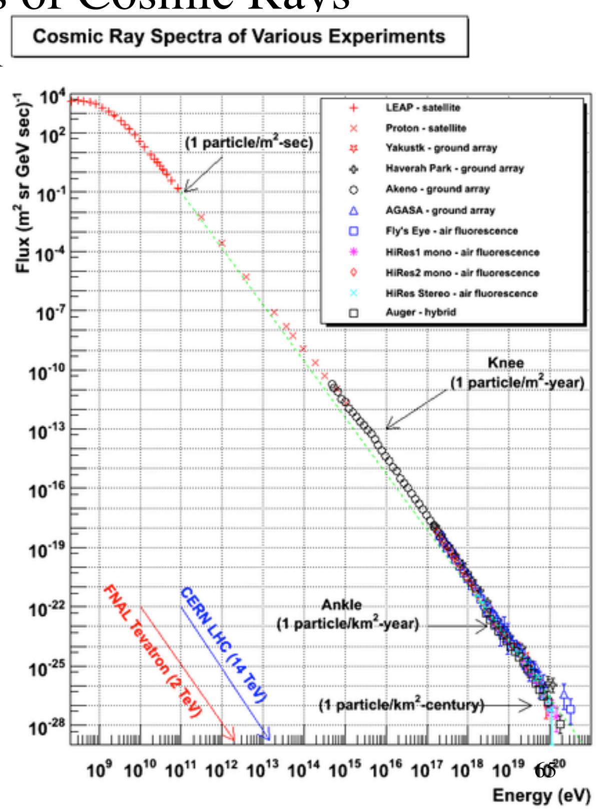
105 Years of Cosmic Rays

- 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



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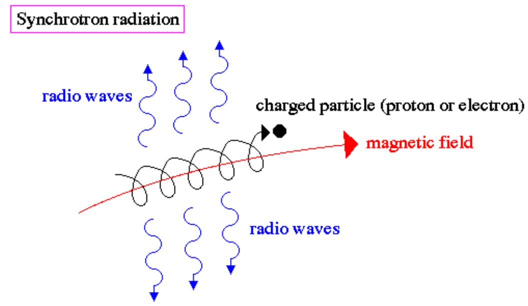
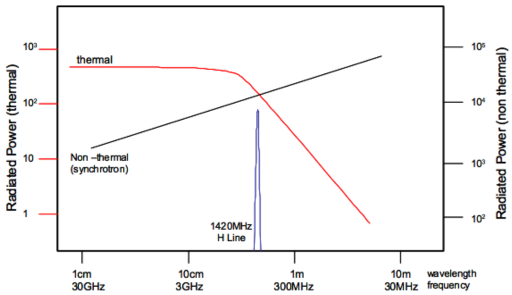
Cosmic Rays

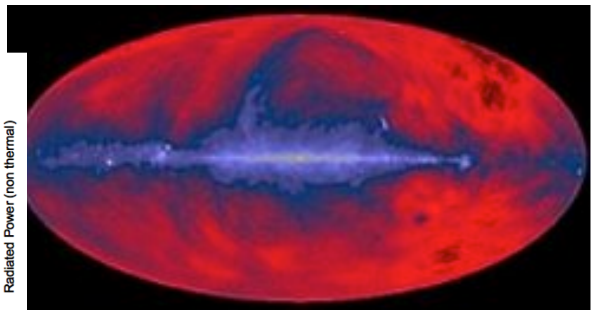
- Have appreciable energy density ~1 eV/cm^3
- Synchrotron emission is convolution of particle spectrum and magnetic field- also emission from 'non-thermal' bremmstrahlung
- Can ionize deeply into molecular clouds



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

radio emission from galaxy





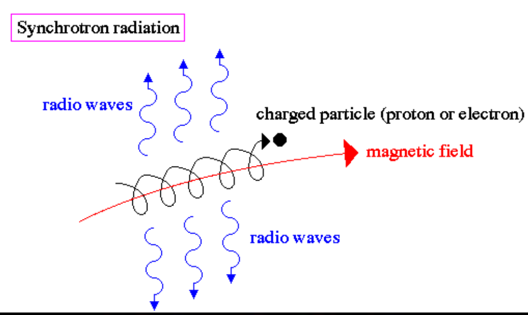
Intensity of radio continuum from MW

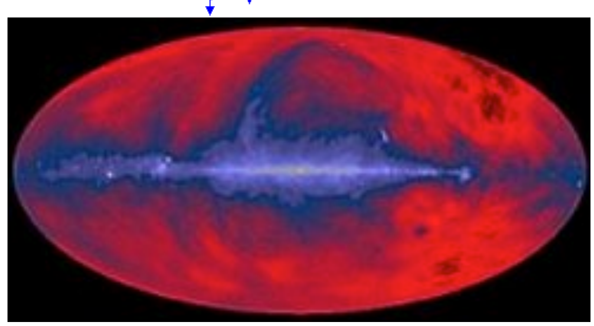
Radio Continuum Emission

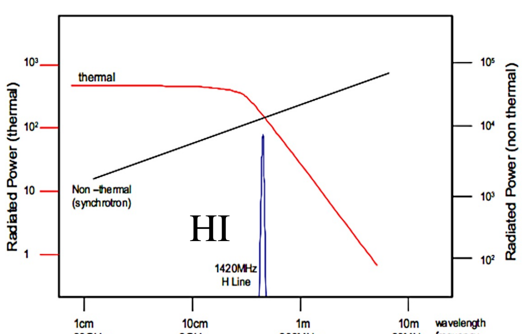
- Synchrotron emission: convolution of particle spectrum and magnetic field-power law spectrum- $F_\nu \sim A\nu^{-\alpha}$

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

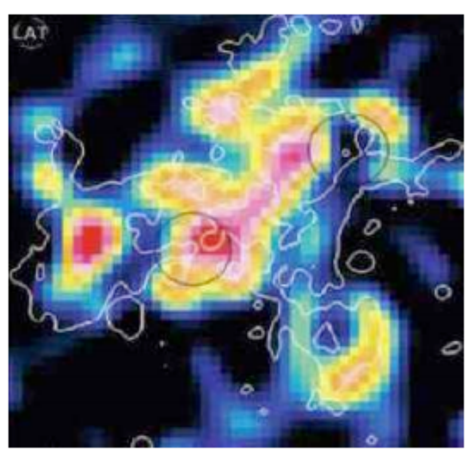


Fig. 2 ~100 pc Cygnus Superbubble in 10-100 Gev γ-Rays from Fermi [11]

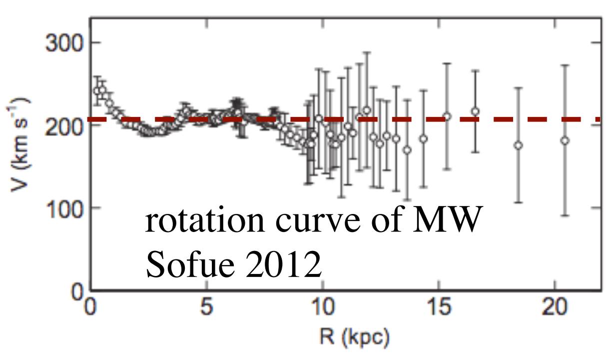
Simple Estimate of Mass of Milky Way

- ... 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_0~8kpc and rotational velocity ~220km/sec
  $M=9\times10^{10}\,M_\odot$ - corresponds to a density of $\sim4\times10^{-3}M_\odot/pc^3$ (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 $\sim2.7\times10^5$ 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

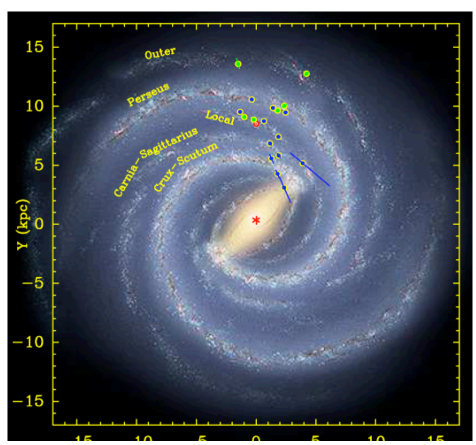
Mass of Milky Way

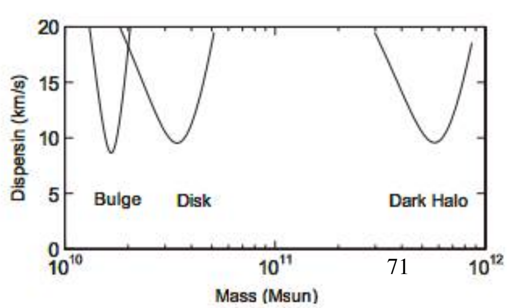
- Rather hard to determine- (the degeneracy between velocity and distance)- use rotation curve fitting and 'proper' potentials
  - absolute distance can be determined for several star forming regions (Reid et al 2009)
  - Partitioning the mass of the MW into bulge, disk and DM halo
-



rotation curve of MW
Sofue 2012

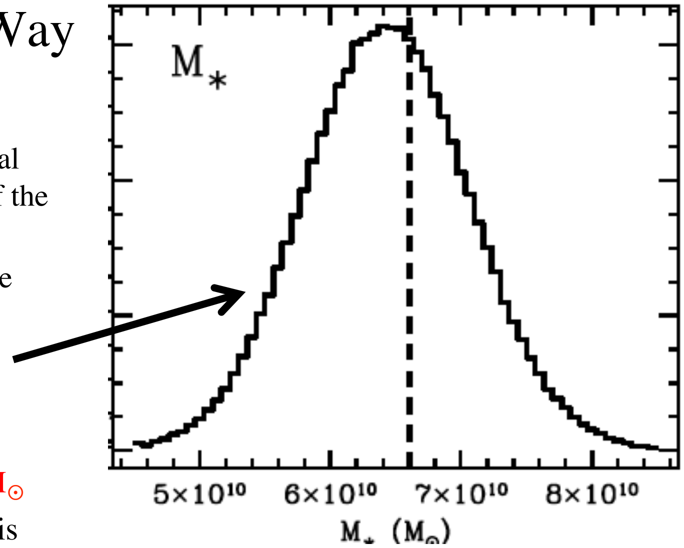
Locations of star-forming regions (dots) artist's Milky Way.





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

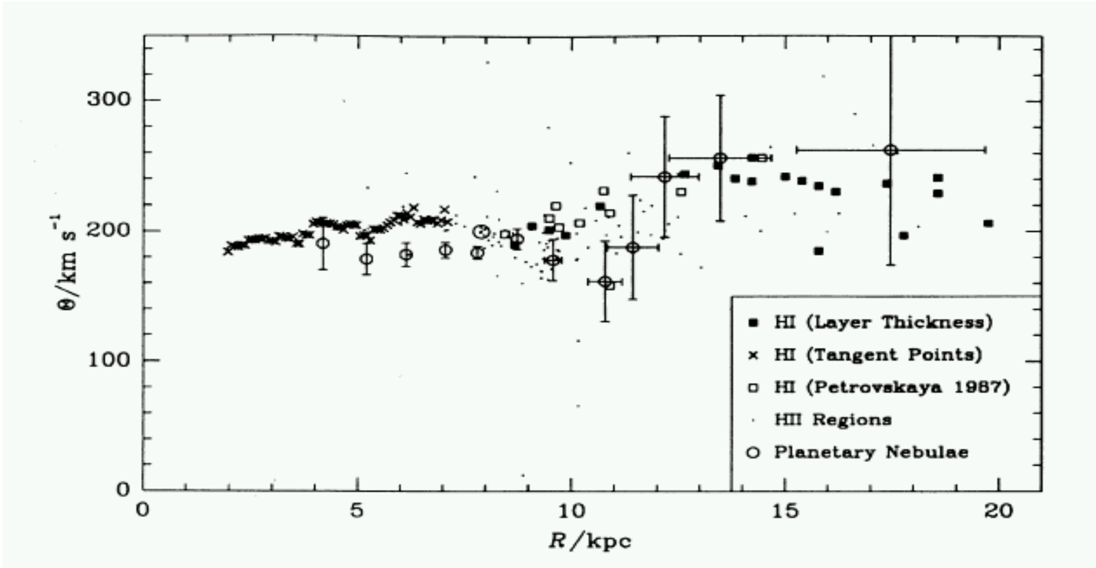
a local dark matter density of $0.40 \pm 0.04 GeV cm^{-3}$ (or in more normal units $0.01\ M_\odot/pc^3$)

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