The motions of stars in the Galaxy

- The stars in the Galaxy define various components, that do not only differ in their spatial distribution but also in their kinematics.
- The dominant motion of stars (and gas) in the Galactic disk is rotation (around the centre of the Galaxy), and these motions occur on nearly circular orbits.
- The stars in the thick disk, rotate more slowly than those in the thin disk. Their random motions are slightly larger.
- The stars in the halo, however, do not rotate in an orderly fashion, their random motions are large, and their orbits are rather elongated.
- Questions we will address today: How do we know this? How can we determine the rotational speed of the nearby disk? How can we best describe the motions of the stars in the different components?

Stellar kinematics and reference frames

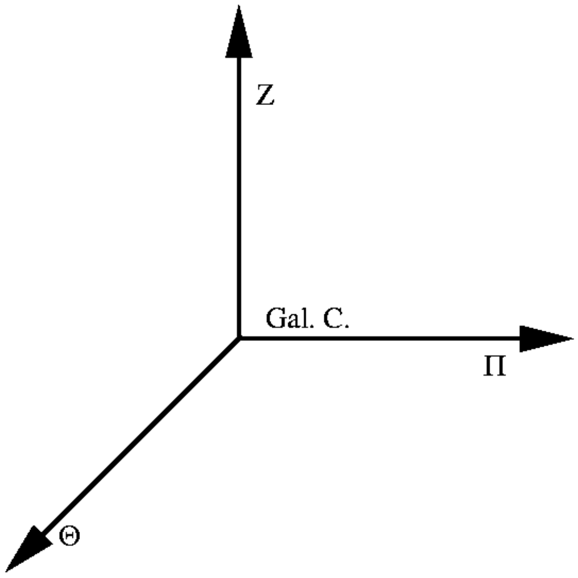
The fundamental Galactic reference frame: is the most important from the point of view of galactic dynamics. It is centered on the galaxy's centre of mass.

The velocity of a star in this reference frame is often given in cylindrical coordinates (Π,Θ,Z) (or (V_R, V_ϕ, V_z)) where

- Π: is along the radial direction (in the Galactic plane), and positive outwards (l=180, b=0)

- Θ: is in the tangential direction (in the Galactic plane), positive in the direction of galactic rotation (l=90, b=0)

- Z: is perpendicular to the galactic plane, and positive northwards



The local standard of rest

•We define a reference system on the Galactic plane that is **moving on a circular orbit** around the Galactic centre, as a **local standard of rest.**

•**"The" local standard of rest** is the reference system located at the solar neighbourhood which moves on a circular orbit.

The SN is a sphere of negligible size centered on the Sun, containing an adequate sample of stars. For example, for disk stars: radius 50-100 pc (1% of the disk size); for stellar halo stars ~ 1 kpc radius (1% of the halo extent).

•It makes sense and it is possible to define such a coordinate system, because a star moving on a circular orbit in the Galactic plane will continue to do so because

- •the Galaxy is axisymmetric, $\Phi = \Phi(R,z)$
- •symmetric with respect to the Galactic plane, $\Phi = \Phi(R,z^{2m})$
- •in steady state (i.e. it is not evolving in time).

•At each point on the Galactic plane, the force that a star feels while moving in the Galactic disk is exclusively radial: $\mathbf{F}(R,z) = -\nabla\Phi(R,z)$

$$\mathbf{F} = -\partial\Phi/\partial R_{z=0}\, \boldsymbol{\varepsilon}_\mathbf{R} - \partial\Phi/\partial z_{z=0}\, \boldsymbol{\varepsilon}_\mathbf{z} = -\partial\Phi/\partial R\,(R)\, \boldsymbol{\varepsilon}_\mathbf{R}$$

which implies that the angular momentum is conserved ($\tau = \mathbf{r} \times \mathbf{F} = \mathbf{0}$).

Galactic rotation

- We have introduced the concept of a reference system that moves on a circular orbit in the Galactic disk (the "standard of rest"), because stars in the Galactic disk move on nearly circular orbits.

- Their motion can be essentially decomposed into a mean rotation around the centre of the Galaxy plus some random motion around this mean trajectory.

- There are essentially two ways in which a disk can rotate:
  - all stars move with the same angular velocity (rigid body rotation)
  - the angular velocity depends on radius: stars closer to the centre complete their orbits in less time that those farther out. This is known as differential rotation.

- Galaxies show differential rotation.

Circular motions and the differential rotation of the disk

- Let us consider the motion of a nearby star located in the Galactic disk moving on a perfectly circular orbit. The velocity of this star with respect to the Galactic centre is $\mathbf{V} = \Omega \times \mathbf{R}$, while the velocity of the LSR is $\mathbf{V_o} = \Omega_o \times \mathbf{R_o}$.

- The **line of sight velocity** of this star with respect to the LSR is

$$v_{los} = (\mathbf{V} - \mathbf{V_o}) \,.\, (\mathbf{R} - \mathbf{R_o})/|\mathbf{R} - \mathbf{R_o}|$$

which we may express in terms of the angular velocity Ω at $\mathbf{R}$ and that at $\mathbf{R_o}$

$$v_{los} = (\Omega \times \mathbf{R} - \Omega_o \times \mathbf{R_o}) \,.\, (\mathbf{R} - \mathbf{R_o})/|\mathbf{R} - \mathbf{R_o}|$$

Using the vector identities $\mathbf{a} \,.\, (\mathbf{a} \times \mathbf{b}) = 0$ and $\mathbf{a} \,.\, (\mathbf{b} \times \mathbf{c}) = \mathbf{b} \,.\, (\mathbf{c} \times \mathbf{a})$, then

$$v_{los} = (\Omega - \Omega_o) \,.\, (\mathbf{R_o} \times \mathbf{R})/|\mathbf{R} - \mathbf{R_o}|$$

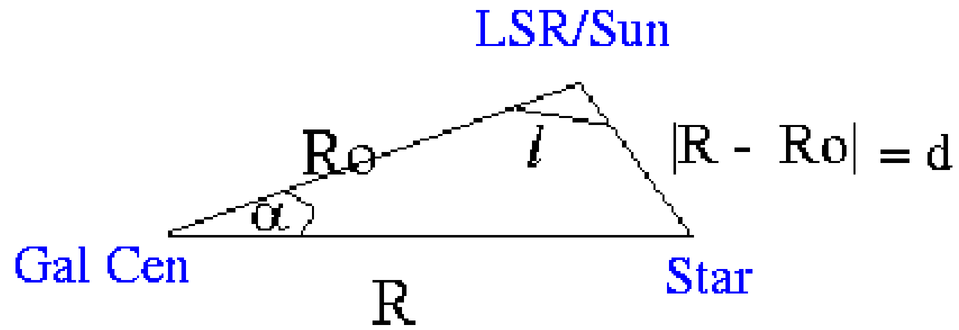
Note that

$\Omega - \Omega_o = -(\Omega - \Omega_o)\,\mathbf{k} = -d\Omega/dR\,|_{R_o}\,(R - R_o)\,\mathbf{k}$

and $\mathbf{R_o} \times \mathbf{R} = -R\ R_o \sin\alpha\ \mathbf{k}$

$= -\mathbf{k}\ R_o\,|\mathbf{R} - \mathbf{R_o}|\,\sin l$

(after using the law of sines)



Therefore the line of sight velocity is

$$v_{los} = d\Omega/\,dR\,|_{R_o}\ (R - R_o)\ R_o \sin l$$

If we approximate $(R - R_o) \sim -\,d \cos l$,

here we have used that $R^2 = R_o^2 + d^2 - 2\,d\,R_o \cos l \sim R_o^2 - 2\,d\,R_o \cos l$, and
$R^2 - R^2_o = (R - R_o)(R + R_o) \sim (R - R_o)\,2\,R_o$,

then $v_{los} = -\,d\Omega/\,dR\,|_{R_o}\ R_o\,d \sin l \cos l$,
or

$\mathbf{v_{los} = A\ d \sin 2\,\mathit{l}}$ where $\mathbf{A = -\,0.5 * R\ d\Omega/\,dR\,|_{R_o}}$

or, in terms of the velocity of a
circular orbit $V_c = \Omega R$

$\mathbf{A = 0.5 * (V_c/R - dV_c/dR)\,|_{R_o}}$

We may proceed in analogous way to describe the proper motion with respect to the LSR of a nearby star moving on a circular velocity. In that case one finds that

$$\mu = B + A \cos 2l$$

where

$$B = -(\Omega + 0.5 * R\, d\Omega/dR)\,|_{R_o} = -\,0.5 * (V_c/R + dV_c/dR)\,|_{R_o}$$

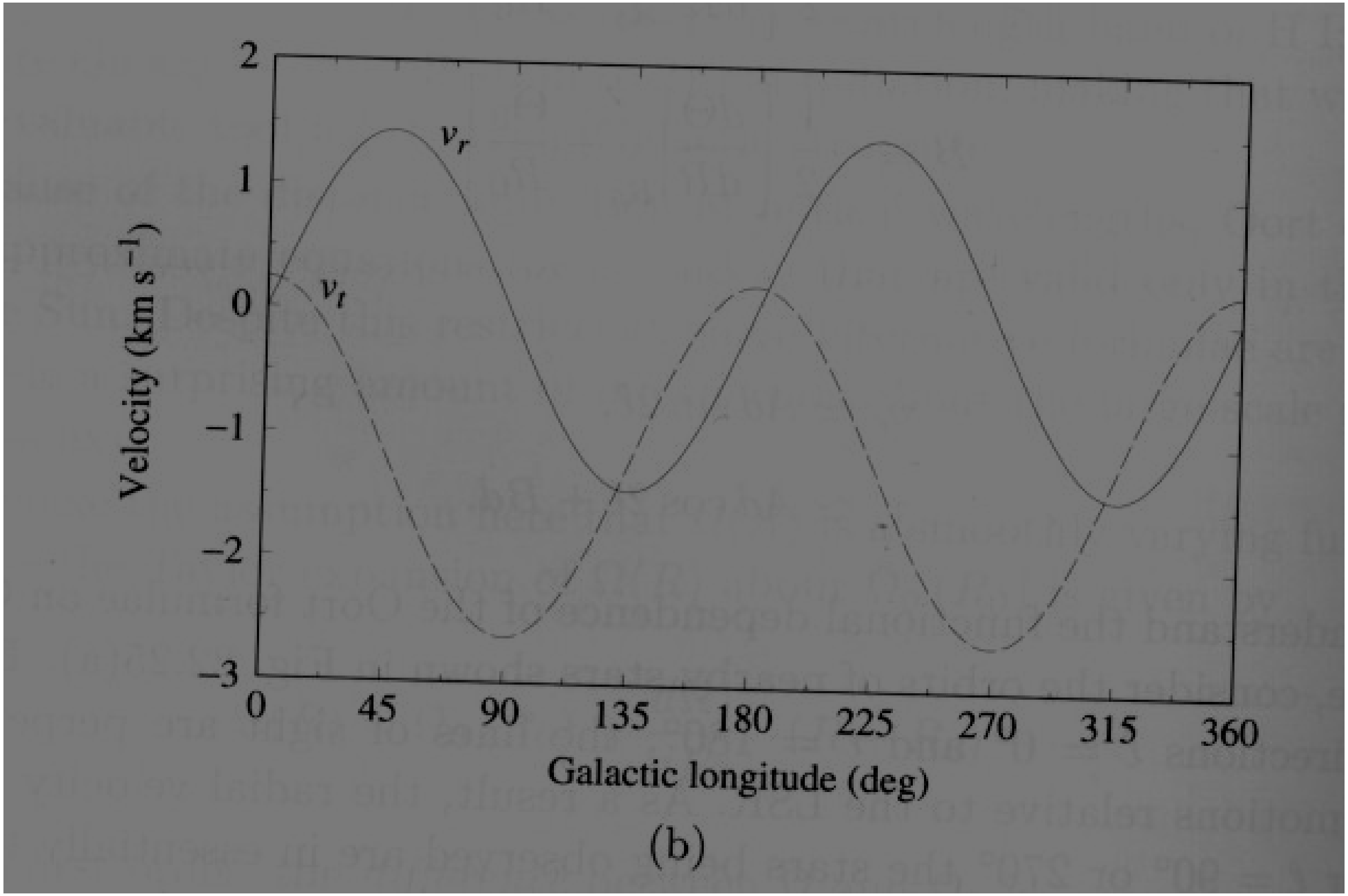
A and B are the Oort constants:

•A measures the shear in the disk, or the deviation from rigid body rotation because it depends on $d\Omega/dR$ (Note that for the rigid body case Ω = const. and $A = 0$).

•B measures the vorticity: the tendency of stars to circulate about a given point

Jan Oort discovered that the motion of stars near the Sun varied with longitude, as described above, and he correctly interpreted as this being due to the differential rotation of the Galactic disk.

Variation of the line of sight and tangential velocities as function of Galactic longitude for stars moving on circular orbits in the Galactic plane



Results

- From observations of the radial velocities and proper motions of nearby stars, it is therefore possible to measure the values of the Oort constants. The most recent determinations give:

$A = 14 \pm 1$ km/s kpc^{-1} $B = -12 \pm 1$ km/s kpc^{-1}

- This implies that it is possible to derive for the Solar neighbourhood the circular velocity and its variation as a function of radius:

$$V_c = R_o\,(A - B)$$
$$dV_c/dR\,|_{Ro} = -\,(A + B)$$

Using the numerical values quoted above, one finds

$$V_c(R_o) = 218\,(R_o/8\text{ kpc})\text{ km/s}$$

Therefore, this method only allows us to derive the value of the circular velocity at the solar neighbourhood if the distance to the Galactic centre is known (and has been derived in some other way)

- Knowledge of the circular velocity and its variation as a function of distance from the Galactic centre is extremely important.

- Recall that for an object orbiting around a point mass (e.g. Earth – Sun system), the acceleration on a circular orbit is

$$V_c^2/r = G\,M/r^2, \text{ or } \quad M = r\,V_c^2/G$$

which implies that if the circular velocity V_c of the object (Earth) is known, as well as its distance to the point mass (1 AU), it is possible to derive the mass M (of the Sun).

- We will see later in the course, that for a spatially extended spherical system, a similar equation holds, where M is replaced by the mass within the radius r, $M = M(<r)$ of the circular orbit.

- For a flattened system, a similar relation holds.

- This implies that it is possible, in principle, to derive how much mass there is inside the orbit of the Sun (or more precisely, the LSR orbit), as well as how this mass is distributed $M = M(r)$ by mapping how V_c varies with radius.

The solar motion

- The stars in the disk do not actually move on perfectly circular orbits, and this is also the case for the Sun.

- This implies that the Sun will move with respect to the local standard of rest (LSR). This motion is known as the “Solar motion”.

- Since the LSR is an “idealized/fiducial” reference frame (there are no stars that exactly follow the motion of the LSR), it is not possible to measure this Solar motion "directly" (i.e. by comparing to what the LSR is doing). In practice, the solar motion is defined with respect to the mean velocity of spectroscopically similar stars (e.g. gK, dM, etc).

- Essentially, we are defining the LSR to have the mean motion of stars (of similar spectral type) in the SN.

- To derive the solar motion we may use radial velocities or proper motions

The solar motion from radial velocities

Let **V** be the velocity of a star in the LSR frame, and $\mathbf{v}_{\mathbf{sun}}$ the velocity of the Sun in the same frame.

Then $< \mathbf{V} > = \sum \mathbf{V}_i = \mathbf{0}$, where the sum is over stars of the same spectral type. This holds by definition of the reference system.

Let us now compute the line of sight velocity of star i:

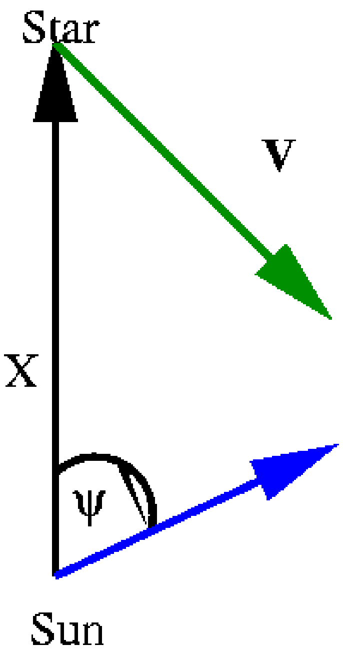
$$v_i^{l.o.s} = (\mathbf{V}_i - \mathbf{v}_{sun}) \,.\, \mathbf{x}_i/|\,\mathbf{x}_i| = \mathbf{V}_i \,.\, \mathbf{x}_i/|\,\mathbf{x}_i| - v_{sun} \cos \psi_i$$

If we average over all N stars,

$$<v^{l.o.s}> = 1/N \,\{\sum v_i^{l.o.s}\} = 1/N \,\{ \sum \mathbf{V}_i \,.\, \mathbf{x}_i/|\,\mathbf{x}_i| - v_{sun} \sum \cos \psi_i\}$$

If we select stars located in the same direction and distance then $\mathbf{x}_i/|\,\mathbf{x}_i| = \mathbf{x}$, and $\cos \psi_i = \cos \psi$. Thus

$$<v^{l.o.s}> = - v_{sun} \cos \psi$$



The line of sight velocity is largest for $\psi = 180$ (receding) and smallest for $\psi = 0$ (approaching). The direction of $\mathbf{v}_{\mathbf{sun}}$ is known as the **apex** of the solar motion, while the opposite direction is the **antapex**.

The solar motion from proper motions

We may express the proper motion vector as a cross product:

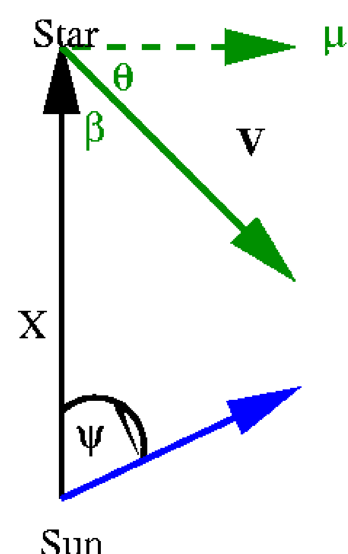
$$\mu_i = 1/d_i * \{(\mathbf{V}_i - \mathbf{v}_{sun}) \times \mathbf{x}_i/|\,\mathbf{x}_i|\} \times \mathbf{x}_i/|\,\mathbf{x}_i|$$

Let us now average over all stars to determine the solar motion:

$$<\mu> = 1/N \, [\, \sum 1/d_i * \{(\mathbf{V}_i - \mathbf{v}_{sun}) \times \mathbf{x}_i/|\,\mathbf{x}_i|\} \times \mathbf{x}_i/|\,\mathbf{x}_i|\,]$$

We again select stars located in the same direction and distance then $\mathbf{x}_i/|\,\mathbf{x}_i| = \mathbf{x}$, and using that $\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = (\mathbf{A.C})\,\mathbf{B} - (\mathbf{A.B})\,\mathbf{C}$

$$<\mu> = 1/d \, \{\mathbf{v}_{sun} - v_{sun} \cos\psi \;\; \mathbf{x}/|\,\mathbf{x}|\}$$



Thus the mean proper motion vanishes in the direction of the apex and of the antapex, and is largest for ψ = 90, 270.

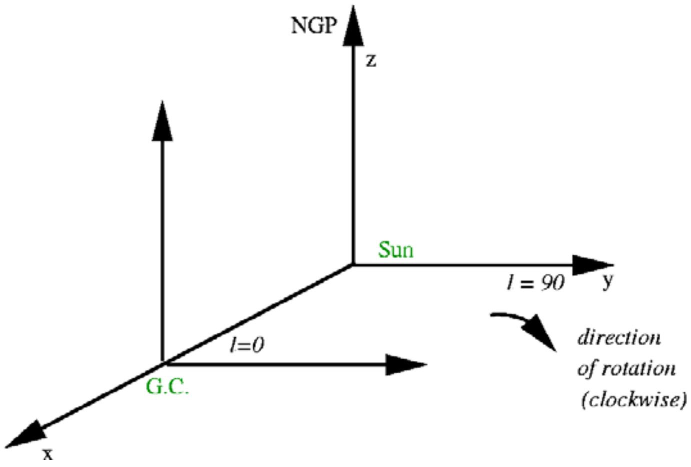
This is true for stars lying in the same direction, even if they are located at different distances. However, to estimate the magnitude of the solar motion one needs to have the distance information to the individual stars.

The solar motion: results

In the LSR reference frame, we define

$(U, V, W) = (v_R, v_\phi - \Theta_{LSR}, v_z)$

as the velocity components of a star (note: this will not include the rotation around the Galactic centre).



Dehnen & Binney (1998) used a sample of nearby disk stars observed with the Hipparcos satellite to determine the Solar motion. They used the fact that the mean velocities of such stars (wrt Sun) should be a reflection of the solar motion:

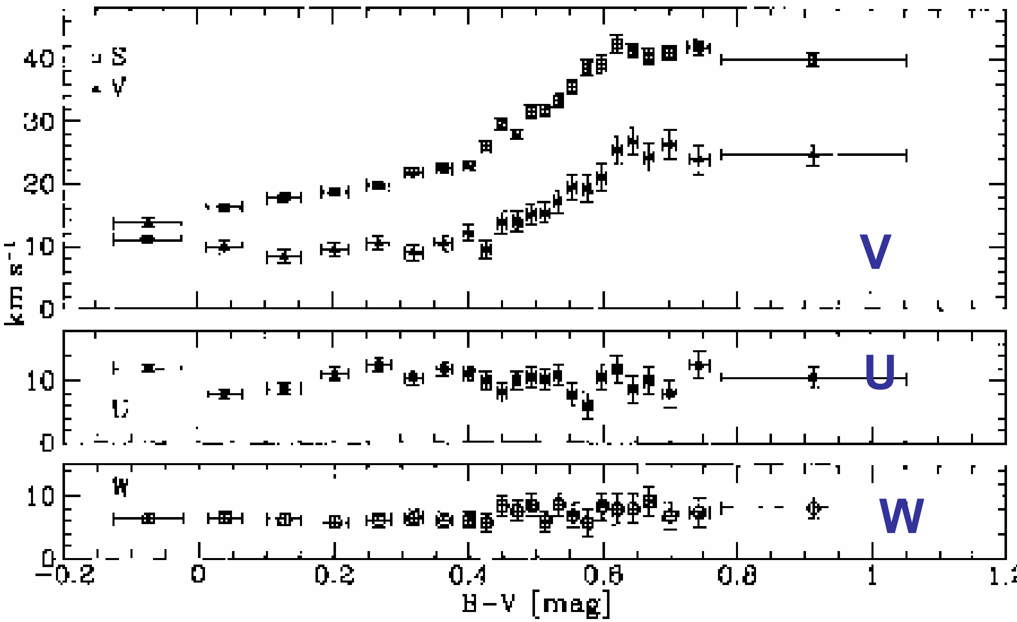
$$<\boldsymbol{v}> = - <\boldsymbol{v}_{sun}>$$

They found

$U_{sun} = 10 \pm 0.4$ km/s

$W_{sun} = 7.2 \pm 0.4$ km/s

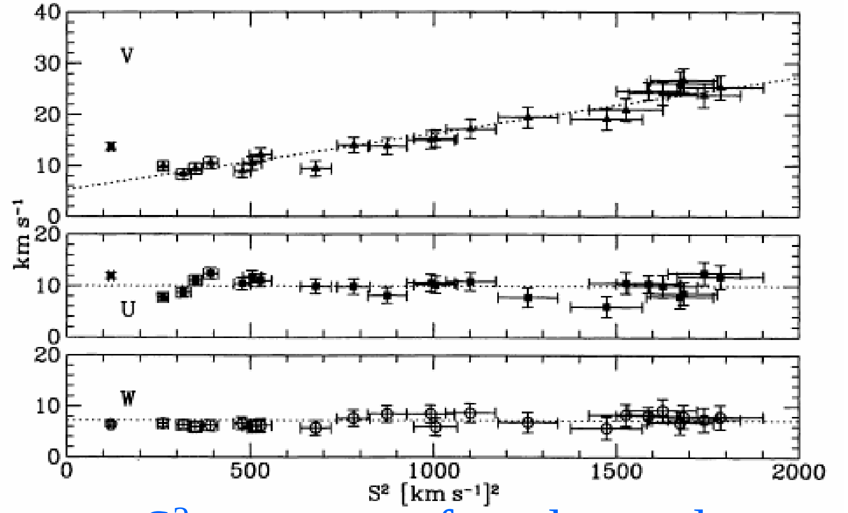
Notice that these are independent of (B-V), while V_{sun} varies with color



V_{sun} correlates with the random velocities of stars in the SN.

The fit to this relation (in the limit of zero velocity dispersion) gives the actual solar motion

V_{sun} = 5.2 ± 0.6 km/s



S^2: measure of random vel

The tendency of the mean rotational velocity of a stellar population to lag behind the LSR is known as asymmetric drift. This phenomenon is reflected in the increase in random motions of the population with the mean rotational velocity.

The Sun is moving towards the Galactic centre, upwards (away from the plane) and faster than if it was moving on a perfectly circular orbit

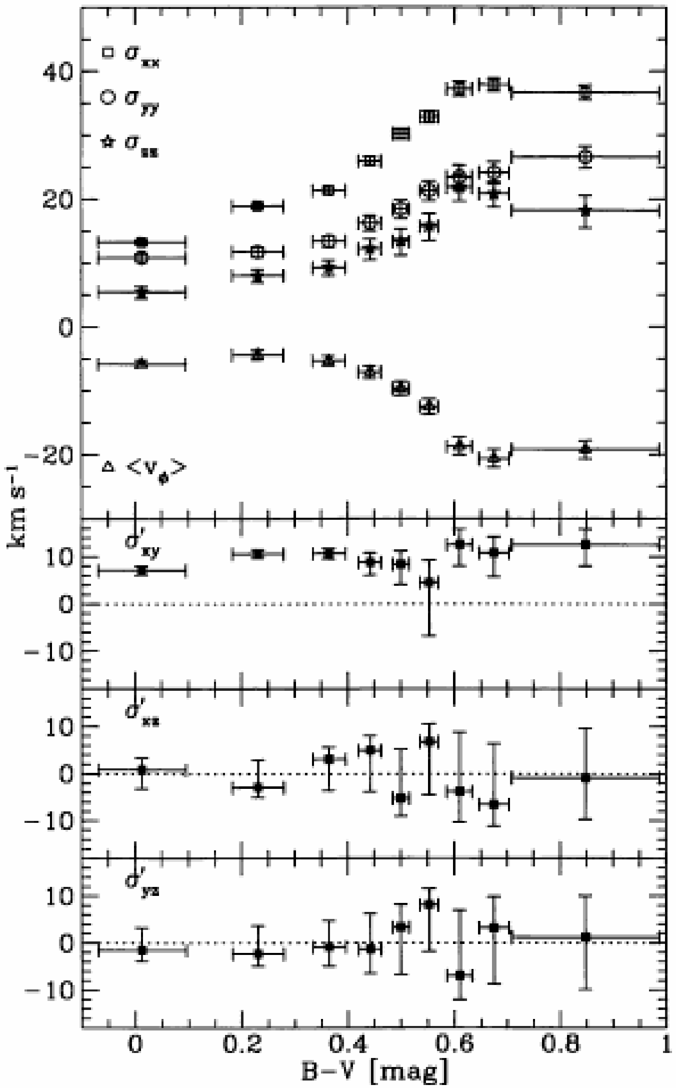
Random velocities of stars

Stars in the Galactic disk have two types of motions:

- "ordered" on nearly circular orbits (around the Gal. Centre, described by the LSR rotation)
- "random" motions, which are best described by the velocity dispersion

$$\sigma_k = \langle (v_k - \langle v_k \rangle)^2 \rangle^{1/2},$$

where $\langle v_k \rangle$ is the mean velocity in the k-direction (k=x,y,z).



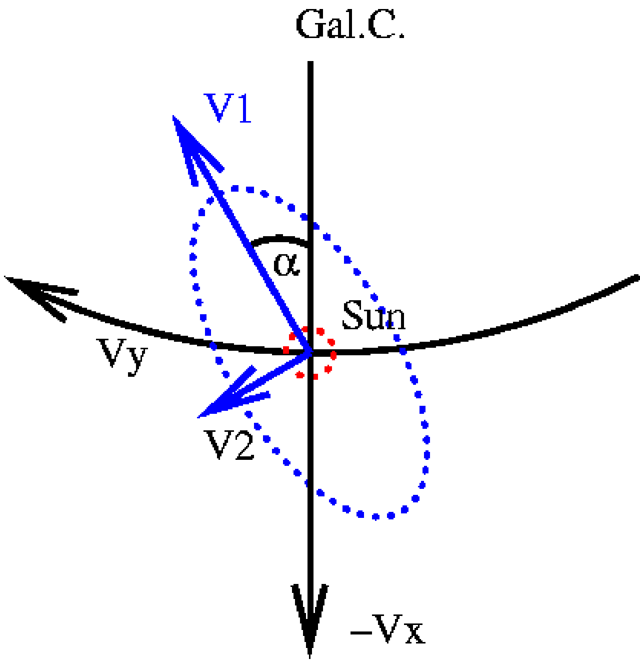
All dispersions increase with color up to (B-V)~0.6

Main sequence stars bluer than (B-V) ~ 0.6 are younger than 10 Gyr, while the red stars are predominantly old.

The increase of σ with (B-V) points at a physical mechanism that operates progressively in time. The orbits of stars suffer from perturbations, due to the graininess of the potential of the Galaxy, e.g. like produced by molecular clouds.

Vertex deviation

In addition to velocity dispersions, one may also compute cross-products: $\langle v_x (v_y - \langle v_y \rangle) \rangle$, …



All products which involve v_z are consistent with zero within the uncertainties, while this is not the case, for the cross products involving the x,y velocity components.

We define a new coordinate system such that

$V_1 = V_x \cos\alpha - (V_y - \langle V_y \rangle) \sin\alpha$

$V_2 = V_x \sin\alpha + (V_y - \langle V_y \rangle) \cos\alpha$.

The angle α is known as the **vertex deviation**.

The fact that the cross products are non-zero, i.e. that α is non-zero, shows that the (x,y,z) coordinates are not the optimal to describe the distribution of velocities of stars in the SN.

The new system of coordinates is referred to as the principal axes coordinate system.
The reason for this becomes clear in the next sheet

Schwarzschild distribution

In a classical gas, the velocities of particles can be described by a Maxwell-Boltzmann distribution.

Schwarzschild pointed out that a similar distribution function could be used to describe the velocities of stars in the SN.

The probability that the velocity of a star lies in

$d^3v = dv_1\ dv_2\ dv_3$ (where $dv_3 = dv_z$) is expressed as:

$$f(\mathbf{v})\ d^3v = d^3v\ /[(2\ \pi)^{3/2}\ \sigma_1\ \sigma_2\ \sigma_3]\ \exp\{-\sum v_i^2/(2\ \sigma_i^2)\}$$

Thus, <u>f(**v**) is constant on ellipsoids in velocity space</u>

Note that this is slightly different from the distribution function used to describe the motions of particles in a gas:

$f(v) = 1/(2\pi\ \sigma^2)^{1/2}\ \exp(-v^2/2\sigma^2)$

because in this case, it is the speed of the particles ($v = |\mathbf{v}|$) what is important, and there is no distinction between the different directions of motion.

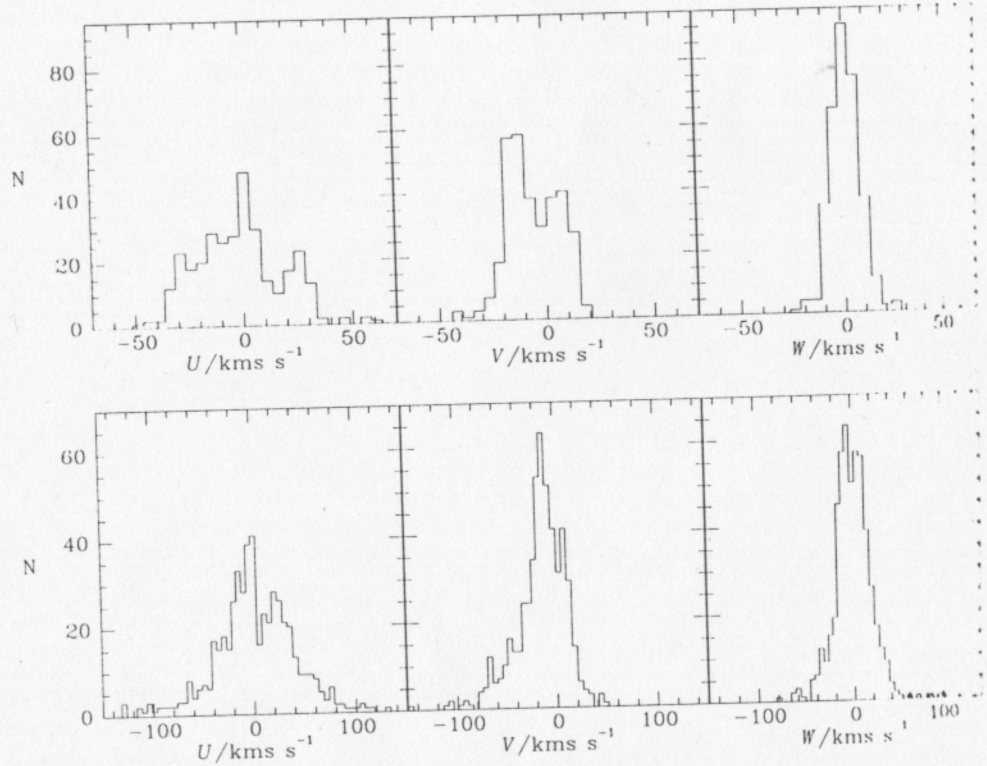
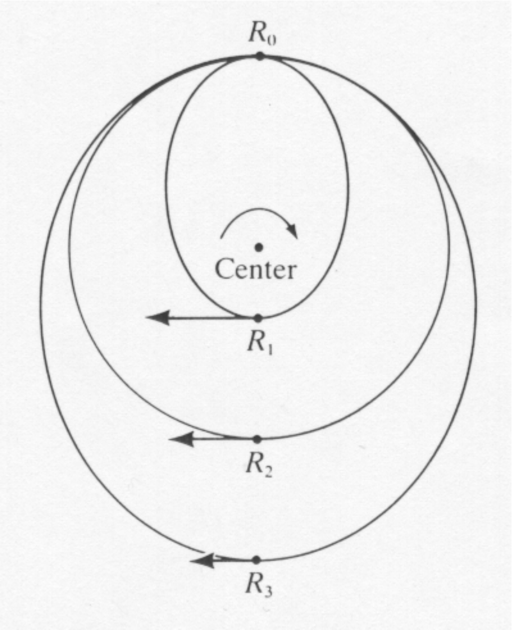


Figure 10.14 Upper panels: histograms of U, V and W for a sample of 323 nearby MS stars of MK type F1 and earlier. Lower panels: similar data for 510 K and M dwarfs. Velocities are with respect to the LSR that is defined by equations (10.11). [From data kindly supplied by H. Jahreiss]

- The velocity distribution of stars in the U and W directions is rather close to Gaussian.
- The distribution in the V-direction is skewed towards negative velocities.

This can be understood as follows:



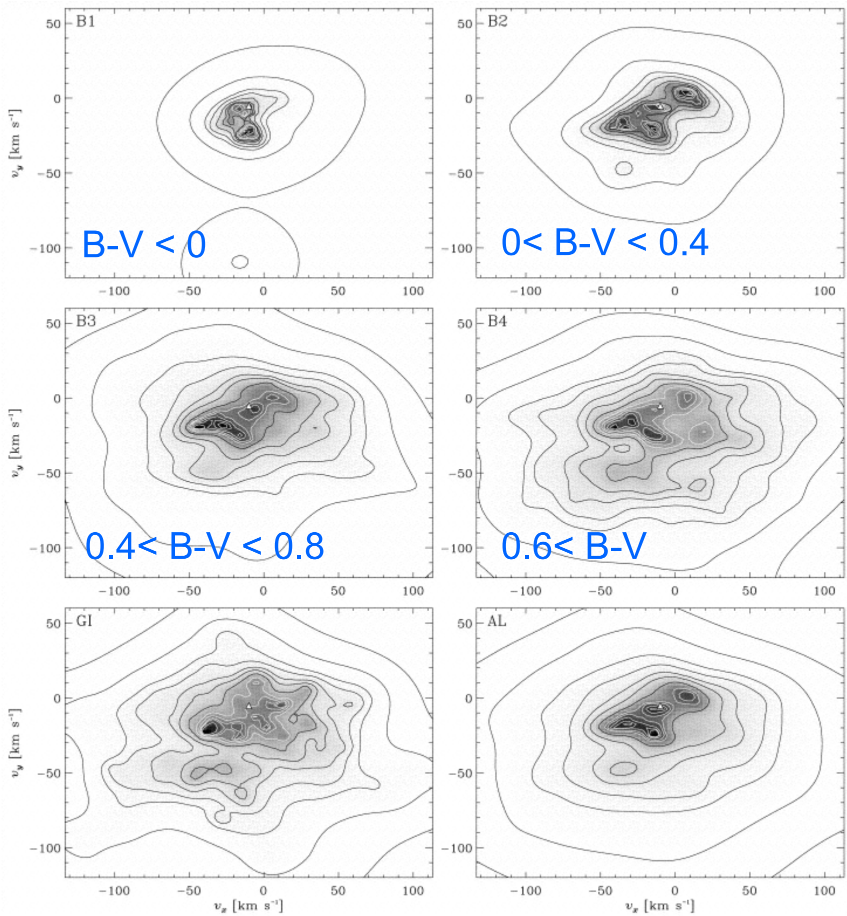
•Stars with V < 0 km/s are located at smaller radii:
since V is the rotational velocity with respect to the LSR, a negative V implies that the star is moving with a smaller tangential velocity than the LSR. Consider a star on an elliptical orbit that oscillates inside the solar circle, that is between R_1 and R_o. At the pericenter R_1, its velocity is purely tangential and is larger than the circular velocity at that point (it needs to reach larger radii): $\Theta(R_1) > \Theta_c(R_1)$. At the apocenter R_o, its velocity is again purely tangential, but now it has to be smaller than the circular velocity $\Theta_c(R_o)$ (since it reaches a smaller radius): $\Theta(R_o = R_{max}) < \Theta_c(R_o)$
Note that the smaller V, the further inside R_o its pericenter is located.

* The density of stars increases exponentially towards the center: there are more stars with V < 0 than with positive V

* The velocity dispersion also increases exponentially towards the center: the probability that a star from $R < R_o$ visits the SN is larger than for a star with $R > R_o$

Star streams

- The distribution of stars in velocity space is not smooth.
- U vs V, V vs W plots show substructures or moving groups



A moving group is a set of stars moving with similar velocities. They are also known as streams

•Streams can often be associated to open clusters or associations, in which case there is also spatial structure. In this case, these are groups of stars that formed together.

•Moving groups also can have dynamical origin (like due perturbations by spiral arms)

The thick disk

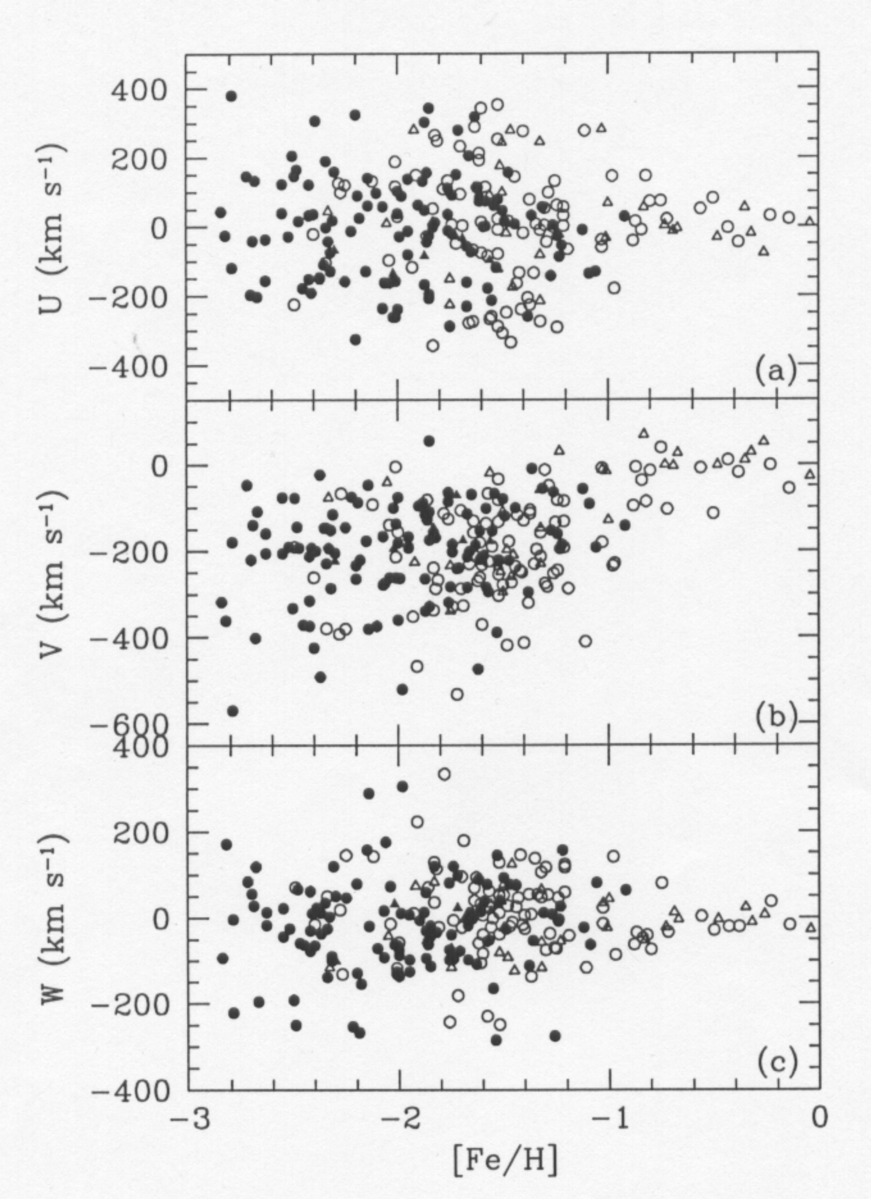
- The thick disk was discovered through star counts, but do its stars have different kinematics than the thin disk stars?

- The velocity dispersions are larger (they have to be if the stars are to reach higher distances above the Galactic plane)

- The rotational velocity of thick disk stars is lower: in the SN typically $\Theta \sim 160$ km/s

Kinematics of halo stars

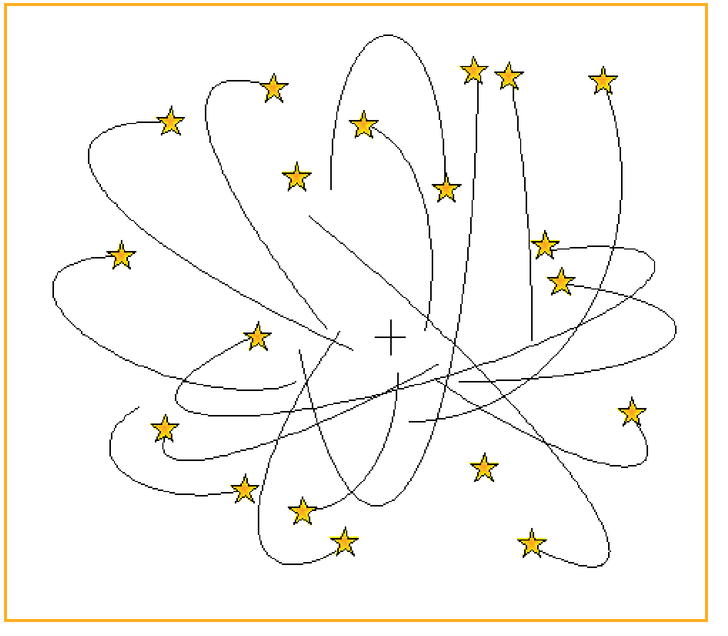
- The velocity distribution of halo stars that pass through the SN is close to Schwarzschild distribution (also known as a multivariate Gaussian).
- The principal axes are closely aligned to the (Π,Θ,Z) directions, and the halo does not rotate
- The velocity dispersions are (140, 105, 95) km/s



•The shape of the velocity ellipsoid (aligned with the radial direction) shows that halo stars are preferentially moving on very eccentric orbits (rather than circular)

•Halo stars can be easily identified in proper motion surveys, because they have quite distinct orbits from the rest of the stars in the disk. Their spatial velocities relative to the Sun are very large, and so are their proper motions.

•The large values of the velocities of these halo stars show that they travel quite far into the halo of our Galaxy. They can be used to estimate the escape velocity (and hence the mass of the Milky Way).



Kinematics of the bulge

- The bulge is not the extension of the stellar halo towards the center of the Galaxy:
  - Besides having a different spatial distribution, its stars have different metallicities (closer to those of the disk)
  - The kinematics are different: bulge stars rotate with a mean velocity of ~ 100 km/s
  - Their velocity dispersions are slightly smaller than those of the stellar halo

Surveys of disk, thick disk, stellar halo and bulge: what criteria?

- We want to define sets of criteria which would enable us to preferentially select stars from a given Galactic component

- Criteria can be based on: spatial distribution (location of fields, etc), color selection (blue, red stars?), kinematics (radial velocities, proper motions), metallicities (high, low, etc)

- Need to be aware that no criterion is perfect and that there will always be some contamination from other Galactic components. Try to keep this to a minimum, and find ways of identifying them.

Gas in the Galaxy. The rotation curve

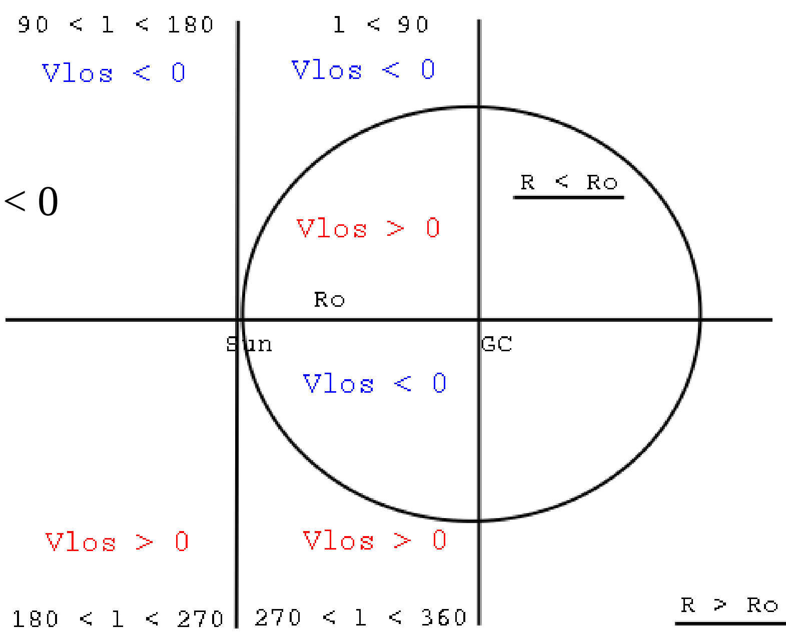
- We have seen that the line-of-sight velocities of nearby disk stars moving on perfectly circular orbits is

  $$v_{los} = R_o\,(\Omega - \Omega_o)\sin l = R_o \sin l\;\;(V/R - V_o/R_o)$$

  Note that if the MW rotated like a rigid body, the angular speed would be constant, and the line of sight velocity would always be zero.

- Typically, **the angular speed drops with radius**
  - recall for example, in the Kepler problem, $V = (GM/R)^{1/2}$, so that $V/R \propto R^{-3/2}$.

- This implies that
  - $0 < l < 90$ and $R < R_o$ (e.g. nearby) : $V_{los} > 0$
  - $0 < l < 90$ and $R > R_o$ (external to the solar circle): $V_{los} < 0$
  - $90 < l < 180$ ($R > R_o$ always) : $V_{los} < 0$
  - $180 < l < 270$ ($R > R_o$ always): $V_{los} > 0$
  - $270 < l < 360$ and $R < R_{o:}$ $V_{los} < 0$,
  - $270 < l < 360$ and $R > R_o$, : $V_{los} > 0$



This very characteristic pattern of radial velocities can be observed in the motion of gas in the disk of our Galaxy.

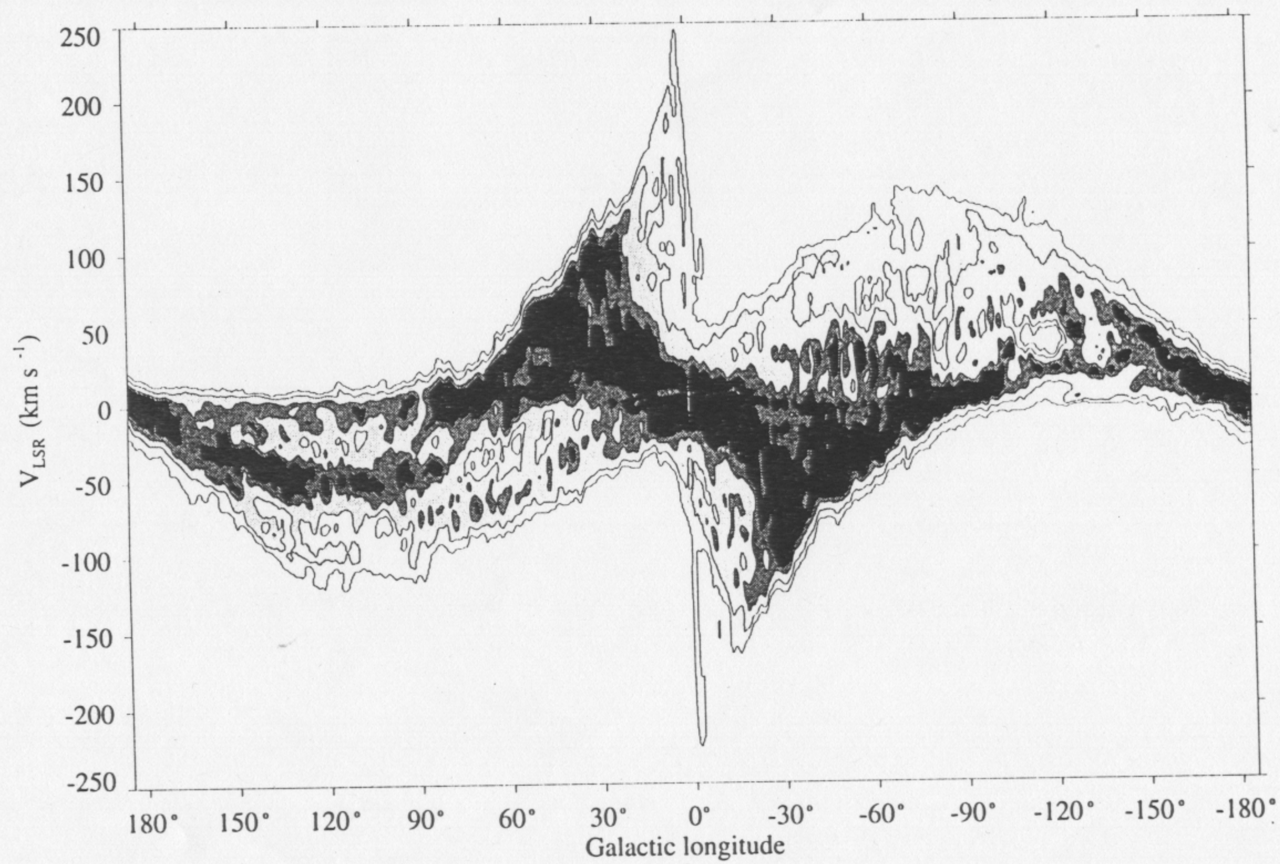


Figure 2.18 In the plane of the disk, the intensity of 21 cm emission from neutral hydrogen gas moving toward or away from us with velocity V_{LSR}, measured relative to the local standard of rest – D. Hartmann, W. Burton.

As expected there is no gas with positive velocities in the 2nd quadrant or with negative velocities in the 3rd quadrant

The rotation curve of the Galaxy

A dynamically interesting quantity to measure is the rotation curve of the Galaxy: how the circular velocity varies as a function of radius in the Milky Way.

In principle, this should be possible using the radial velocities and proper motions of stars in the disk of our Galaxy (as we already discussed). However, the light of stars in the disk is strongly absorbed by dust.

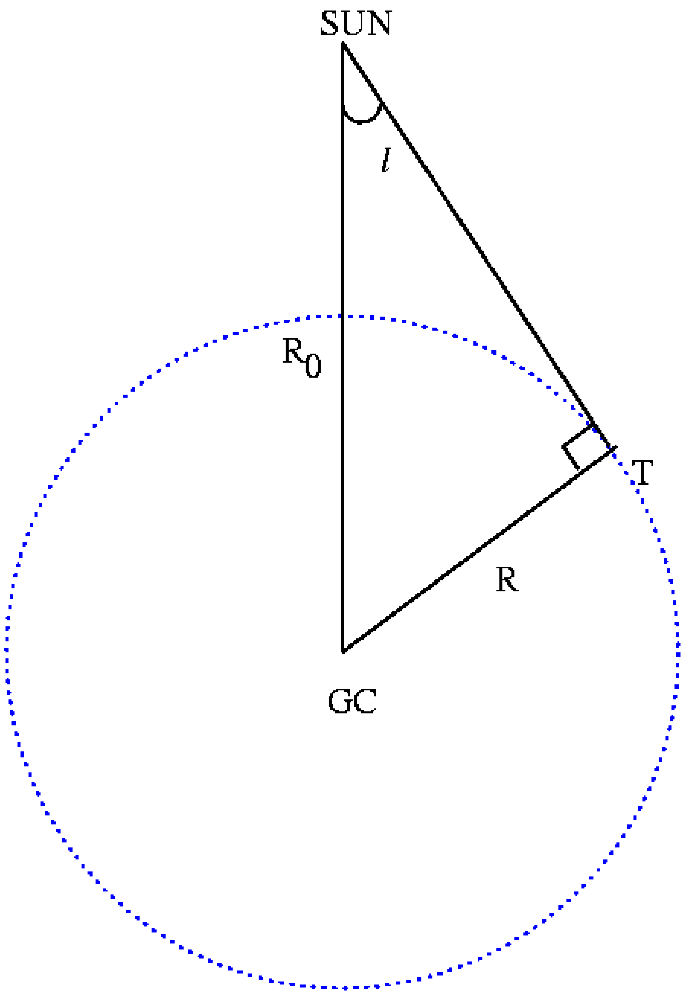
We can however, use the HI gas which emits in the radio and is not affected by dust.

The problem in this case is that it is usually impossible to know the distance to the emitting gas.

Tangent-point method

It can be used to determine the circular velocity of gas in the inner Galaxy ($R < R_0$). It uses the fact that the angular speed decreases with radius. In the direction $0 < l < 90$, the l.o.s. velocity is greatest at the tangent point T

Here the line of sight direction is perpendicular to the vector to the Galactic centre, and hence this line of sight is parallel to the tangential velocity at that point, which is just the circular velocity.



For the tangent point T:

$$R_T = R_0 \sin l$$

and

$$V_{los} = R_0 \sin l \, (V_T/R_T - V_0/R_0) = V_T - V_0 \sin l$$

therefore

$$\Theta_c = V_T = V_0 \sin l + V_{los}$$

The rotation curve of the Galaxy: results

We can thus derive the circular velocity by measuring the largest velocity where emission from HI is observed for each longitude.

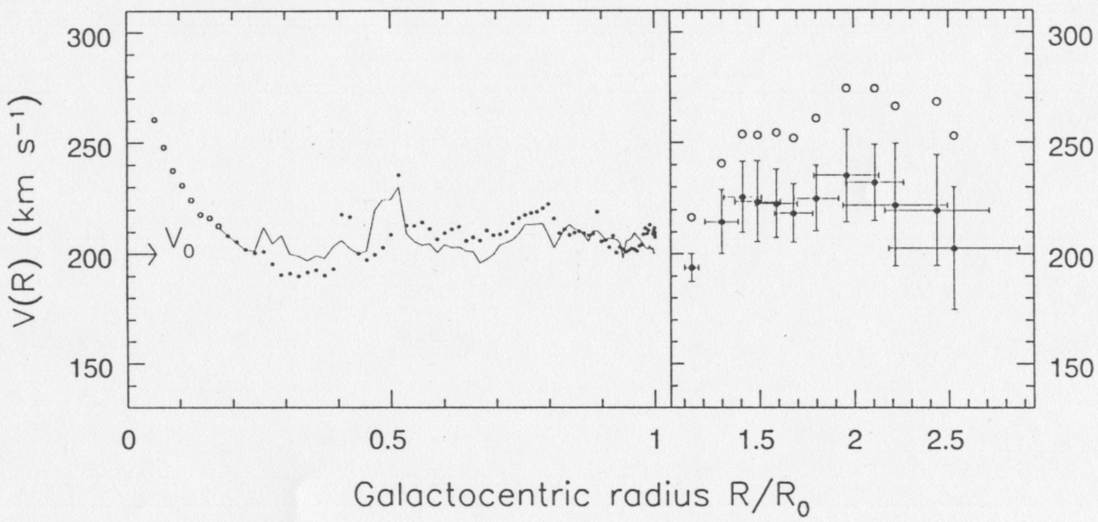


Figure 2.19 Left, Milky Way's rotation from the tangent point method, taking $V_0 = 200\,\mathrm{km\,s^{-1}}$; dots show velocities of northern HI gas with $l > 270°$, while the curve gives results from southern gas at $l < 90°$. The tangent point method fails at $R \lesssim 0.2 R_0$ (open circles) because this gas follows oval orbits in the Galactic bar. Right, rotation speed of the outer Galaxy, calculated for $V_0 = 200\,\mathrm{km\,s^{-1}}$ (filled circles) and for $V_0 = 220\,\mathrm{km\,s^{-1}}$ (open circles); crosses show estimated errors – W.B. Burton, M. Honma.

Note that the variation of V(R) is not completely smooth. This is due to the presence of spiral arms whose gravitational pull on the HI gas can induce velocity changes of the order of 10-20 km/s. Thus if the tangent point is located close to a spiral arm, the velocity measured will differ from the average speed of a circular orbit at that radius.

- The determination of the circular velocity in the outer Galaxy is more difficult (since the distance to the gas is unknown).

- It is possible to use distances to cepheids, young stellar associations (obtained from spectroscopic or photometric parallax methods, etc.), and measure their radial velocity from the emission lines of cold or hot gas around these stars.

- Such distances are sufficiently accurate to show without doubt that the rotation speed V(R) does not decline much in the outer Galaxy, and even that it may be rising.

- As mentioned briefly today, the circular velocity at a given radius V(R) is related to the mass interior to that radius M(<R) by
  $M(< R) = R\, V^2/G$

  Since V(R) does not decline, this means that the mass of the Milky Way must increase almost linearly with radius, even in the outer Galaxy where there are many fewer stars observed.

  This discrepancy between the light and the mass is a common phenomenon in spiral galaxies. Galaxies presumably contain a large amount of matter that does not emit any light: this is the infamous dark-matter.

The gas distribution in the Galaxy

It is not possible to derive distances to individual gas clouds. However, if the rotation curve of the Galaxy is known, we can use the relation between the V_{los} and V(R) to derive the distance R.

This is called a kinematic distance. It enables us to derive how the HI is distributed in the disk of the Milky Way.

The next plot shows the surface density distribution of HI gas and of H_2 (which is derived assuming that CO traces it; the problem is that H_2 has no transitions in the radio or sub-millimeter which would make it directly detectable).

Notice that the distributions of atomic and molecular H are quite different:

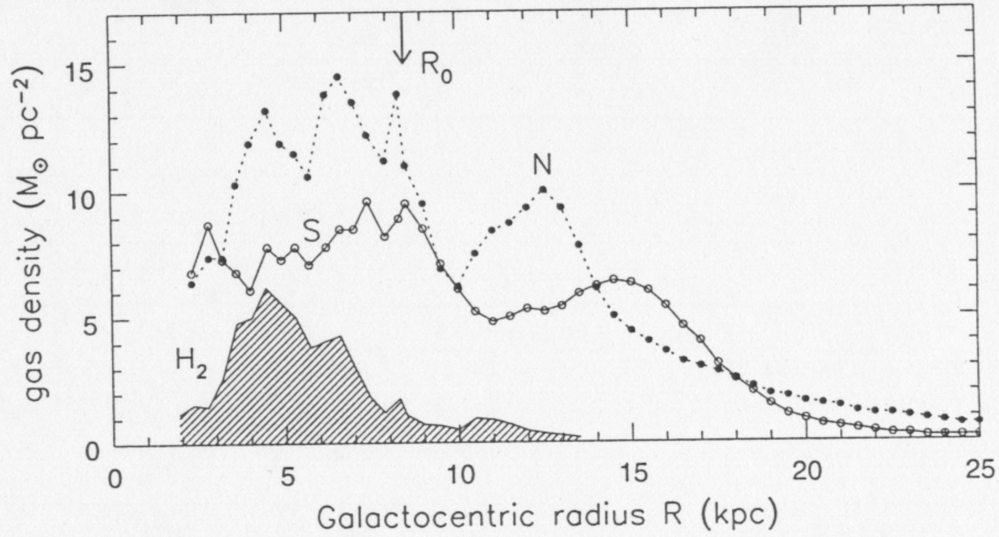


Figure 2.20 Surface density of neutral hydrogen, as estimated separately for the northern ($0 < l < 180°$; filled dots) and southern ($180° < l < 360°$; open circles) half of the Galaxy. Within the solar circle, the density is sensitive to corrections for optical thickness; outside, it depends on what is assumed for $V(R)$. The shaded region shows surface density of molecular hydrogen, as estimated from the intensity of CO emission – W. Burton, T. Dame.

- almost all CO seems to lie inside the solar circle
- only 20% of all HI in the disk is inside R_{sun}
- CO seems to be concentrated in a ring at ~ 4 kpc from the Galactic centre, and to have a central hole
- HI spreads out further than the stars in the disk, and also seems to have a central hole.
- The north and southern distributions of HI are not exactly the same.
- Beyond the solar circle, the HI starts to warp towards b > 0 on the side of *l* = 90, and it bends southwards near *l* = 270.