Structure of Our Galaxy
The Milkyway

More background
Stars and Gas in our Galaxy

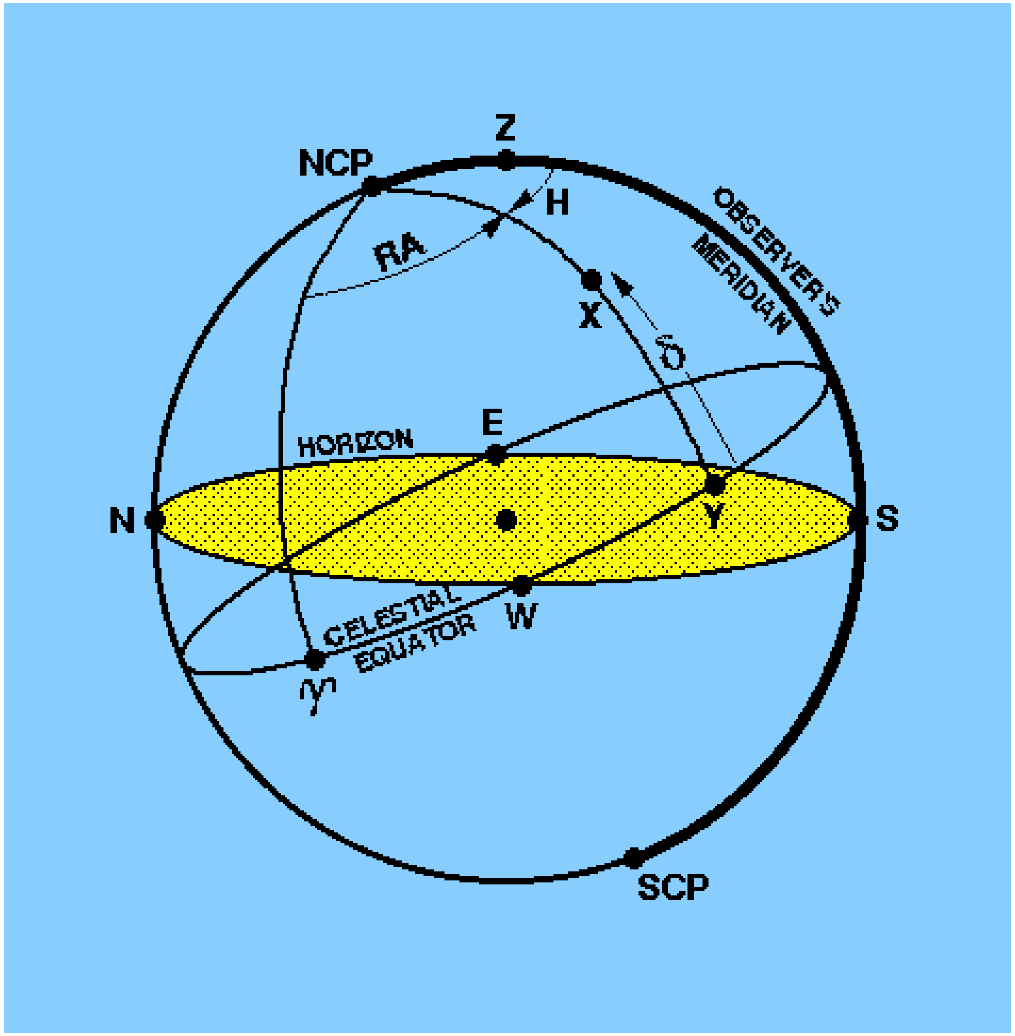
"What good are Mercator's North Poles and Equators
Tropics, Zones, and Meridian Lines?"
So the Bellman would cry, and the crew would reply
"They are merely conventional signs"

L. Carroll -- The Hunting of the Snark

Coordinate systems are used to get around the sky, and to describe the positions of objects. There is no one best system; different systems may be more suited for specific applications. Any basic astronomy textbook has a description of coordinate systems. See Lang's "Astrophysical Formulae", sections 5.1.2 and 5.1.5 for more details, including equations for coordinate conversions.

Equatorial coordinate system

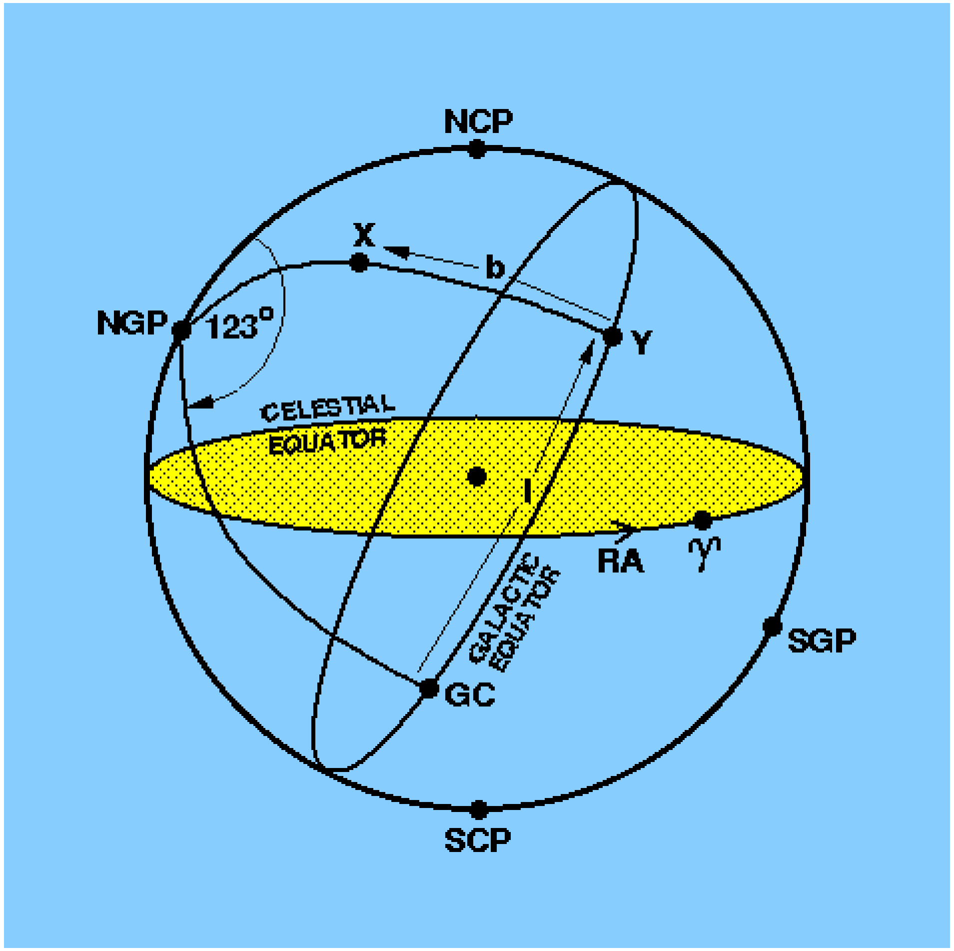
A convenient system to determine the position of a source is one based on the celestial equator and the celestial poles and defined in a similar manner to latitude and longitude on the surface of the Earth. In this system, known as the equatorial coordinate system, the analogue of latitude is the declination, . The declination of a star is its angular distance in degrees measured from the celestial equator along the meridian through the star. It is measured north and south of the celestial equator and ranges from 0° at the celestial equator to 90° at the celestial poles, being taken to be positive when north of the celestial equator and negative when south.

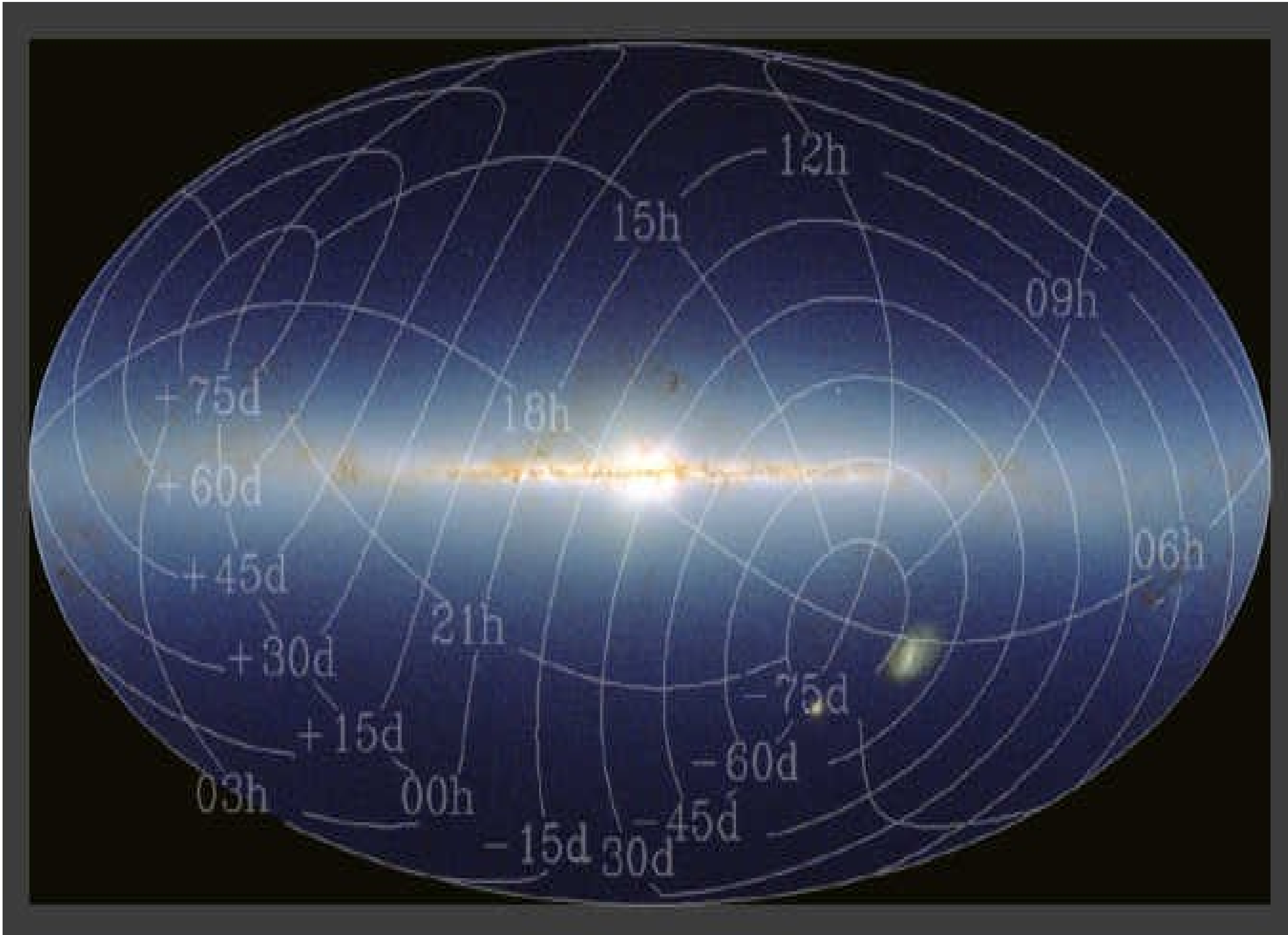


Galactic coordinate system

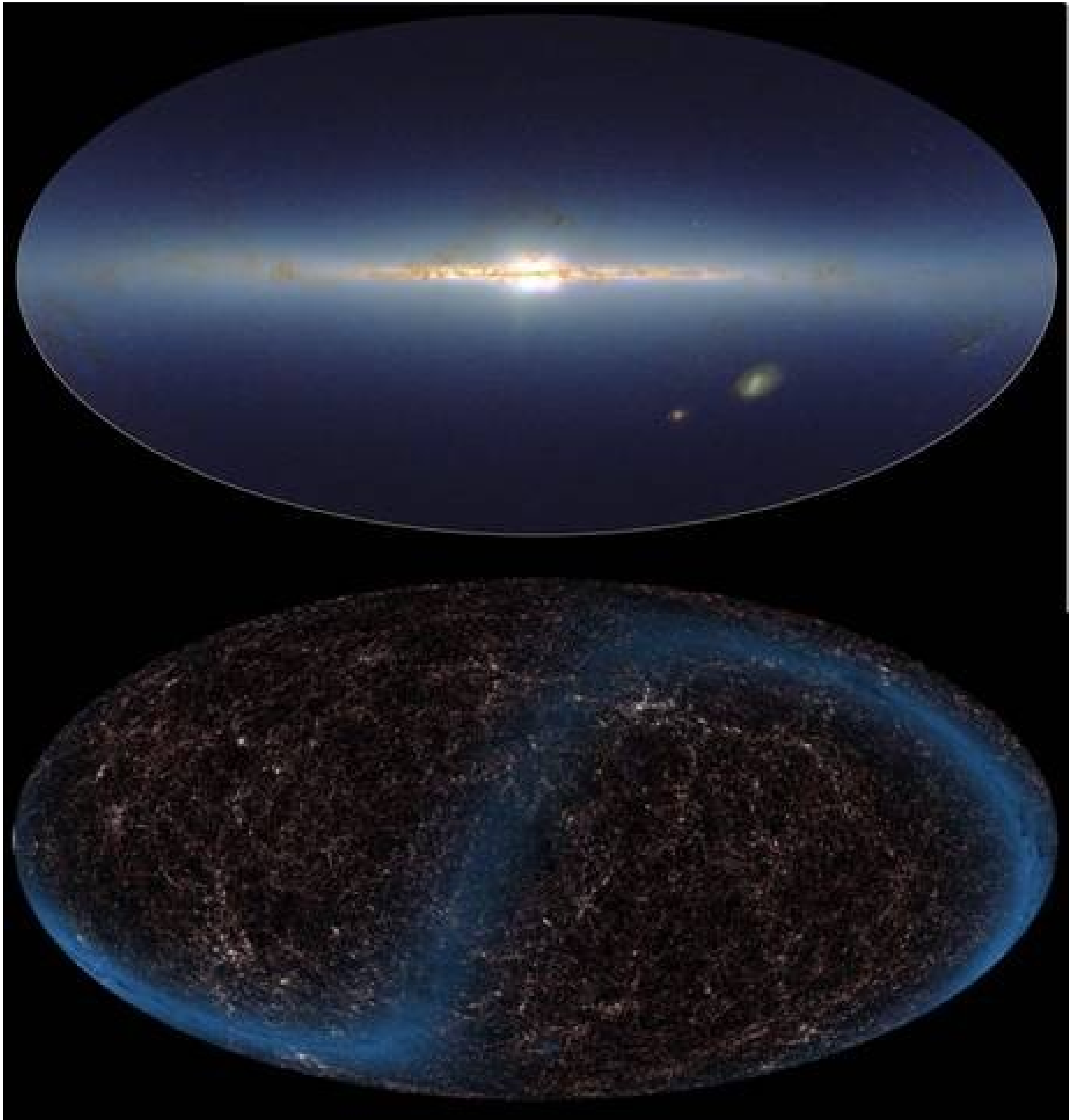
The reference plane of the galactic coordinate system is the disc of our Galaxy (the Milky Way) and the intersection of this plane with the celestial sphere is known as the galactic equator, which is inclined by about 63° to the celestial equator.

Galactic latitude, b, is analogous to declination, but measures distance north or south of the galactic equator, attaining +90° at the north galactic pole (NGP) and -90° at the south galactic pole (SGP). The galactic latitude of the star X in the figure is arc YX and is north.





12h
15h
09h
+75d
18h
+60d
06h
+45d
21h
+30d
−75d
+15d
−60d
03h
00h
−45d
−15d
30d



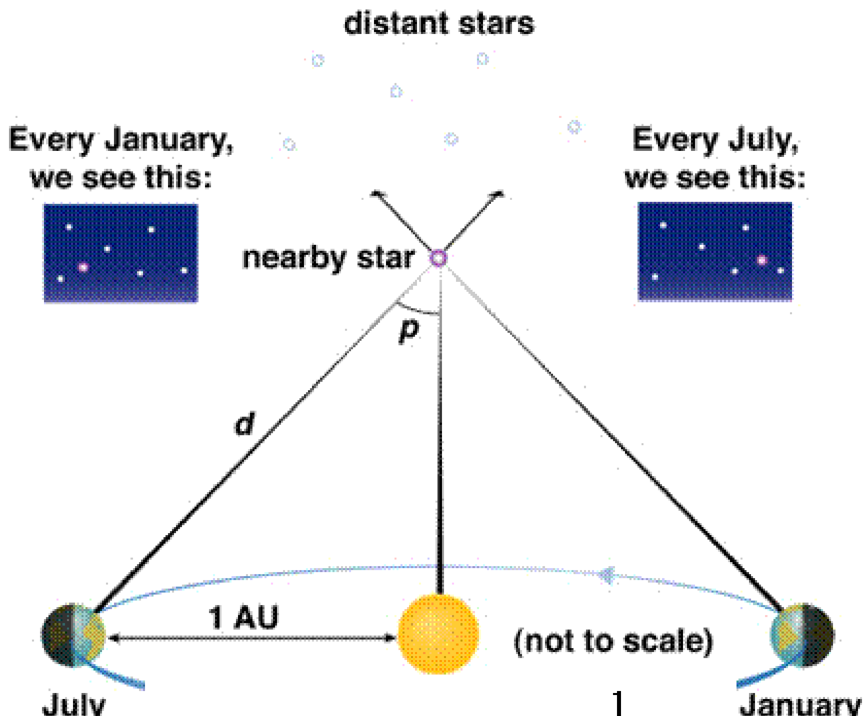
Measuring the distances to Stars

For nearby stars we can use parallax.

The HIgh-Precision PARallax COllecting Satellite (HIPPARCOS)determined parallaxes of 118,218 stars out to a distance of ~500 pc.

1pc = 2.06×10^{5} au = 3.09×10^{18}cm

What about more distance stars?

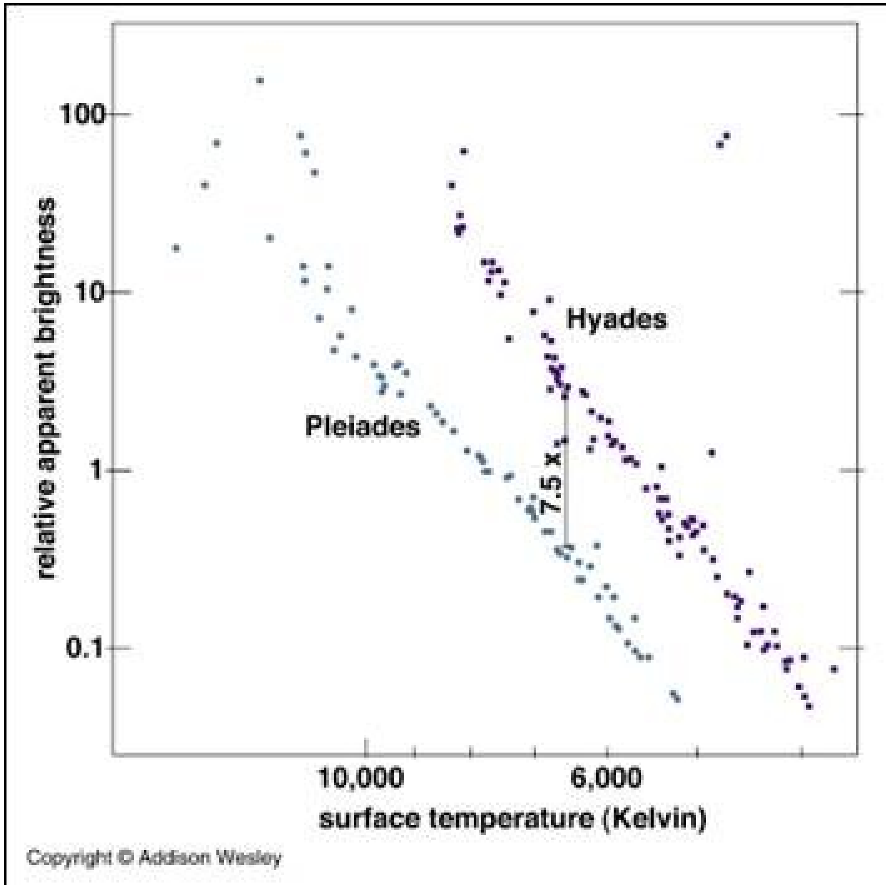


$$\text{Distance (in pc)} = \frac{1}{p(\text{arcsecs})}$$

$$1\ \text{pc} = 3.26\ \text{ly} = 3.09 \times 10^{13}\ \text{km}$$

Main Sequence Fitting

- MS fitting depends on you knowing the distance to at least one cluster. HIPPARCOS has measured the distance to the Hyades cluster accurately and it is often used as the reference cluster.
- You make an H-R diagram of each cluster and then you shift the unknown cluster so that the MS overlays that on the reference cluster.
- Here the Pleiades are about 7.5x dimmer than the Hyades. So the Pleiades are 2.75 times ($7.5^{½}$ times) more distance. (remember F ~ $1/d^2$).



Spectroscopic Parallax

- Take a spectrum of a star to determine its position on the H-R diagram
- measure the apparent magnitude, m
- Once we know its position on the HR diagram we can infer its absolute magnitude, M
- Now knowing m from measurement and inferring M we can use the distance modulus equation:
- $m - M = 5 \log(d/10)$ (eqn 2.2)

γ Crucis is an M3 III star with a measured m_v = 1.63

m-M = 2.43

$\log(d/10) = (m-M)/5$

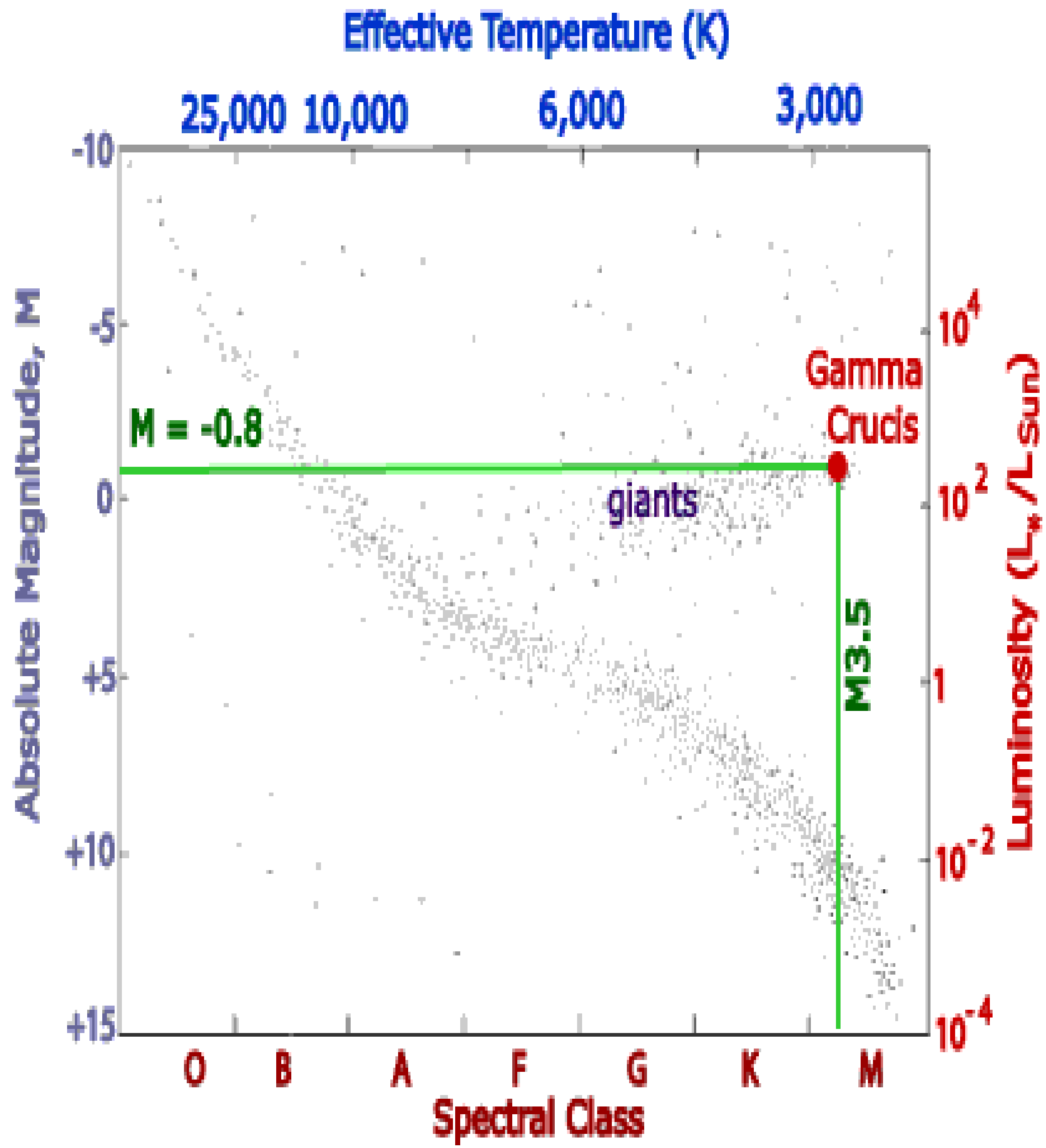
$d/10 = 10^{(m-M)/5}$

$d = 10 \times 10^{(m-M)/5}$

$d = 10 \times 10^{2.43/5}$

$= 10 * 3.06$

$= 30.6$ pc



Spectroscopic Parallax for Gamma Crucis

Measuring Distance with Variable Stars

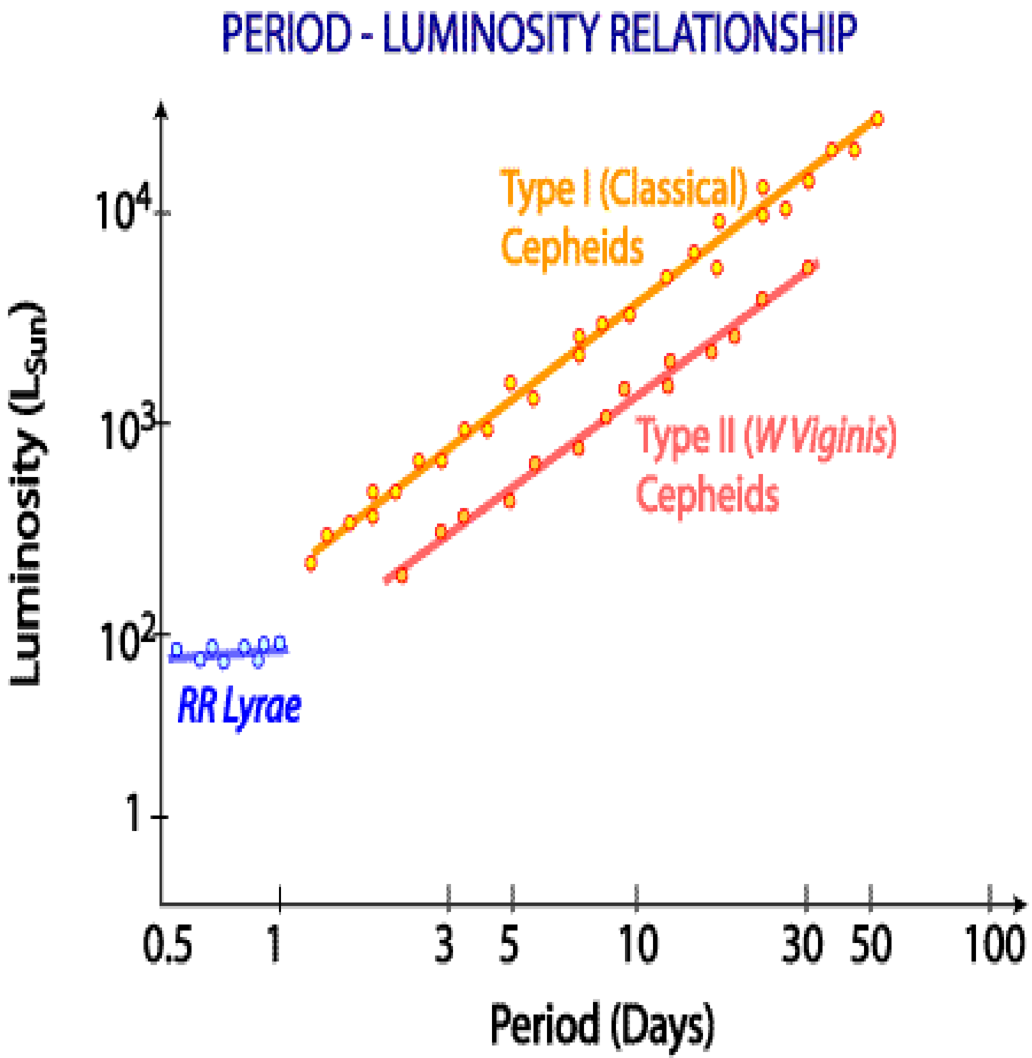
Cepheid variables are named after the star Delta Cephei, the fourth brightest star in the constellation Cepheus. Cepheids are high mass stars nearing the end of their lives (-Cepheid is ~ 5 solar masses). They have with helium cores and regularly expand and contract. They have periods from 2 to 60 days and range in brightness from 300 to 40,000 L_{sun}.

RR Lyrae variables are named after the star RR Lyrae, in the constellation Lyra. They have periods from 4 hrs to 24 hrs and have luminosities of about 80 L_{sun}.

Period Luminosity Relationship

Henrietta Leavitt (1868 - 1921), working at the Harvard College Observatory, studied photographic plates of the Large (LMC) and Small (SMC) Magellanic Clouds and compiled a list of periodic variables, 47 of these were Cepheid variables. She noticed that those with longer periods were brighter than the shorter-period ones. She concluded that since the stars were in the same distant clouds they were all at about the same relative

distance from us. Any difference in apparent magnitude was therefore related to a difference in absolute magnitude.



Salpeter IMF

The Initial Mass Function for stars in the Solar neighborhood was determined by Salpeter in 1955. He found: (M) = $_0M^{-2.35}$

$_0$ is the local stellar density

Using the definition of the IMF, the number of stars that form with masses between M and M + M is:

(M) M To determine the total number of stars formed with masses between M1 and M2, integrate the IMF between these limits:

$$N=\int_{M_1}^{M_2}\xi(M)\,dM=\xi_0\int_{M_1}^{M_2}M^{-2.35}\,dM$$

$$=\xi_0[M^{-1.35}]_{M_1}^{M_2}=\frac{\xi_0}{-1.35}[M_1^{-1.35}-M_2^{-1.35}]$$

Salpeter IMF cont.

To find the total mass of stars between M_1 and M_2:

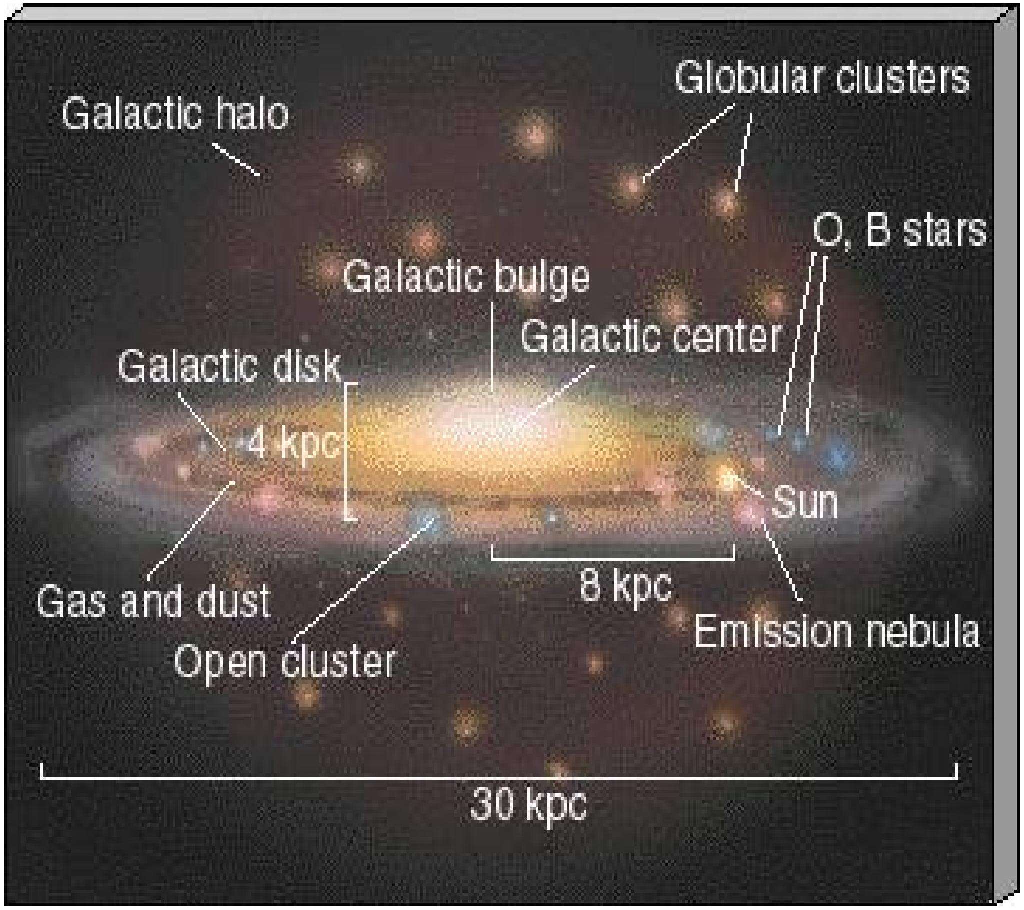
$$M_* = \int_{M_1}^{M_2} M\,\xi(M)\,dM$$

•Most numerous stars are low mass
•Most of the total mass is from low mass stars
•Most of the luminosity is from high mass stars (in a young population)

Observations suggest that the Salpeter function works for $M > 0.5\ M_{sun}$. Below that it must “flatten” so that the mass in stars remains finite.

Structure of the Milkyway

- Bulge is fairly spherical and contains mostly old stars
- Disk - this is where most of the young stars and gas can be found
- Halo - contains globular clusters and most of the dark matter.



MW Disk

What does the structure of the MW disk look like?

1st a local look.

Credit & Copyright: John P. Gleason, Steve Mandel

MW Disk cont.

- How do we determine what stars are in the MW?

By taking a census of stars in the direction of the NGP and using a model to predict what should be seen we can construct the stellar population.

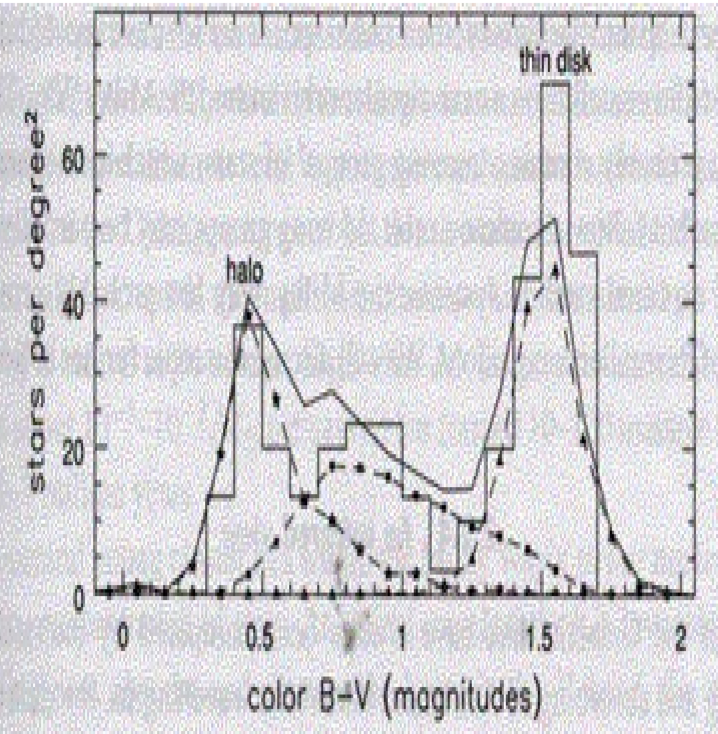


Figure 2.15 Number of stars at each $B - V$ color with apparent V magnitude $19 < m_V < 20$, per square degree near the north Galactic pole. The solid line shows the prediction of a model; thin disk stars (triangles) are red, halo stars (stars) are blue; and thick-disk stars (squares) have intermediate colors – N. Reid.

- Measure the distances to stars by looking up and down out of the plane of the Galaxy. (using spectroscopic parallax)
- Plot the distribution of each spectral type vs distance.
- Fit the distribution with a function of the form

$$n(R, z, S) = n(0,0,S)\exp(-R/h_R(S))\exp(-|z|/h_z(S))$$

- h_R is the scale length
- h_Z is the scale height

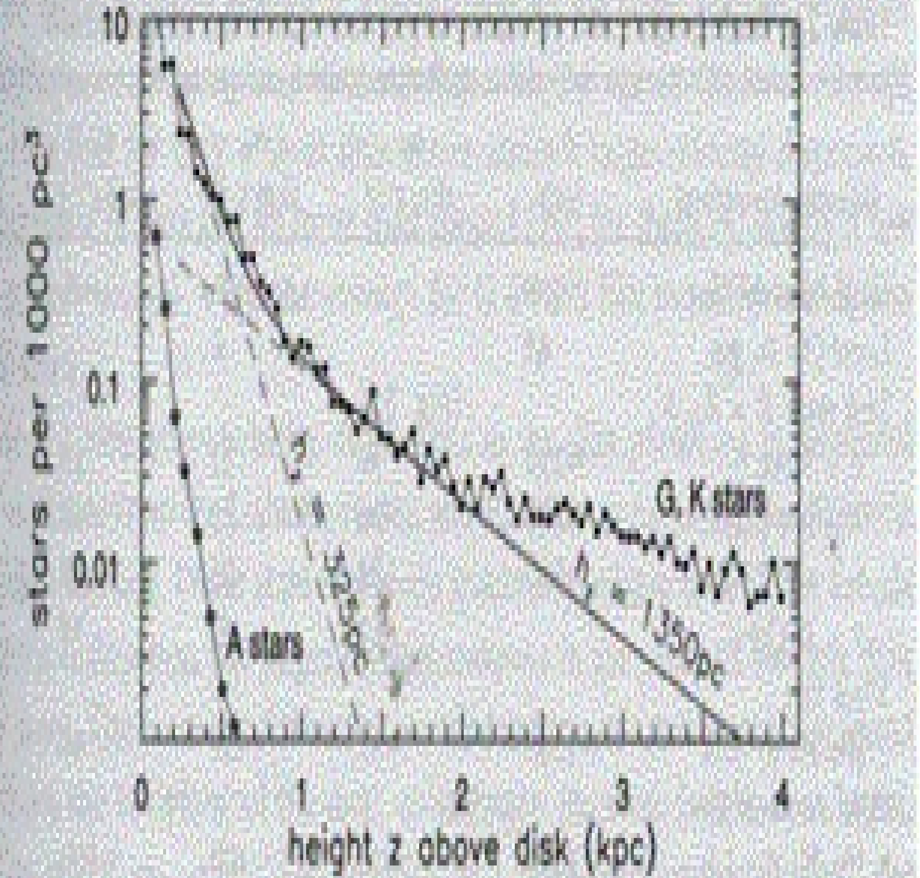


Figure 2.7 Looking toward the south Galactic pole, filled circles show the density of stars with $5 < M_V < 6$; these are late G and early K dwarfs. Sloping dashed lines show $n(z) \propto \exp(-z/325\,\mathrm{pc})$ (thin disk) and $n(z) \propto \exp(-z/1350\,\mathrm{pc})$ (thick disk); the solid curve is their sum. At $z \gtrsim 2$ kpc, most stars belong to the metal-poor halo. A dwarfs (star symbols) lie in a very thin layer – N. Reid, J. Knude.

Typical Scale Heights

Near midplane:

- G, K stars 300-350 pc (thin disk)
- A stars ~200 pc
- HI gas <150 pc
- Molecular gas 60 - 70 pc

Outside the midplane:

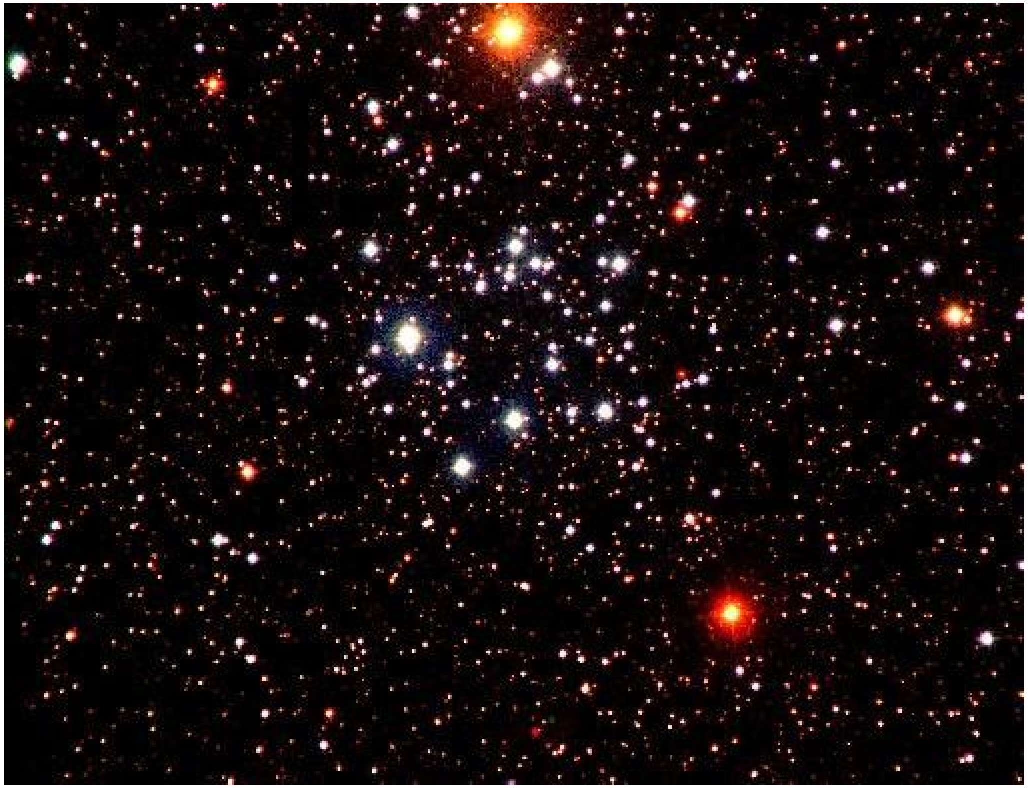
- G, K stars ~1350 pc (thick disk)
- After that we are outside the disk and in the Halo

Stellar Populations

- Young Stars
  - Open Clusters
    - Form from the same mass of gas
    - Coeval (same age)
    - Similar metallicity (~solar)
    - At best loosely bound by gravity
  - Young Disk Stars
    - From disrupted clusters
    - Metallicity ~solar

Stellar Populations cont.

- Old Stars
  - Globular Clusters
    - Formed in the first 1-3 billion years of the collapse of the Galaxy
    - Coeval
    - Similar metallicity (0.1 - 10^{-4} solar)
    - Tightly bound by gravity
  - Individual Stars
    - Similar to Globular Clusters
    - Not bound together by gravity

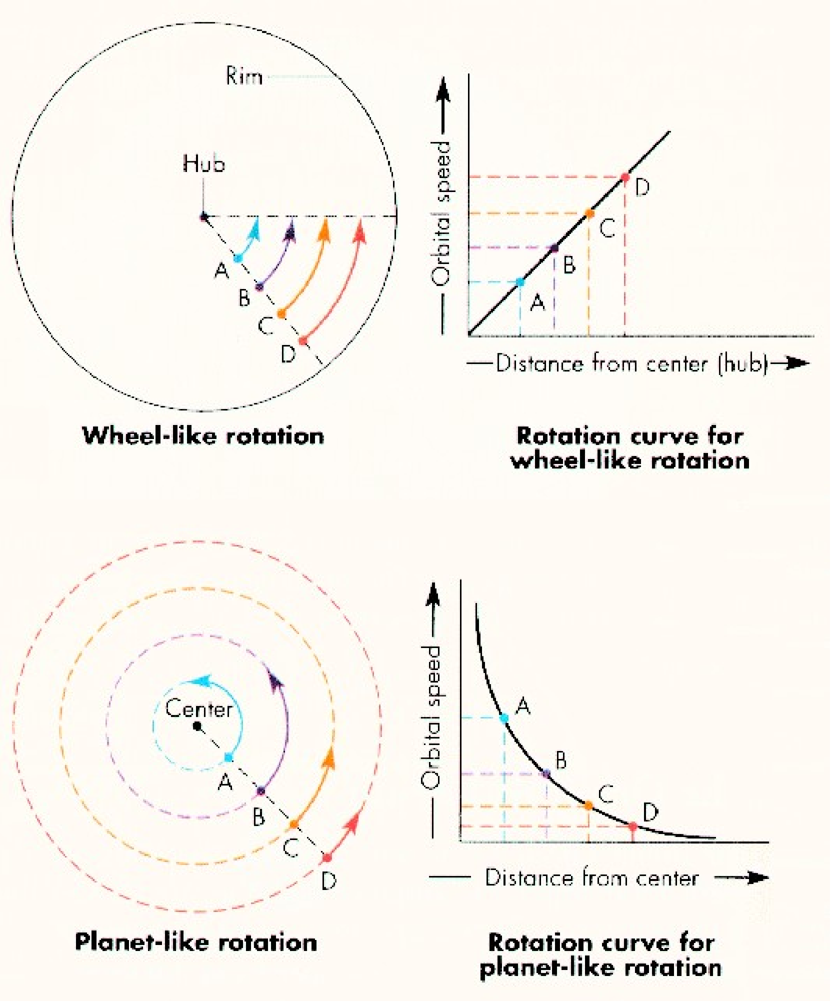


Open Cluster: M50 APOD

Globular Cluster: M3 APOD

Galactic Rotation

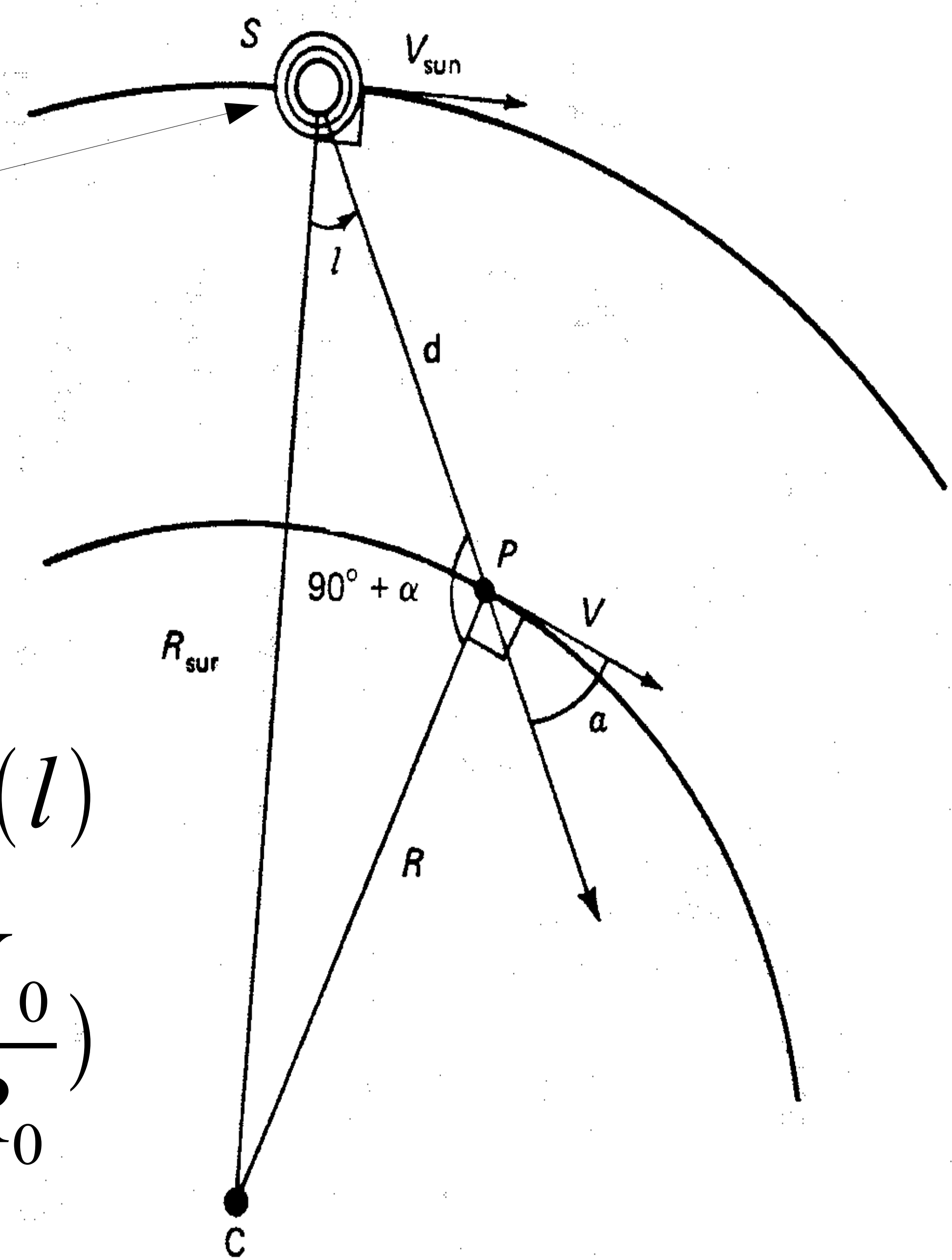
- The Galaxy rotates differentially
  - Stars closer to the center rotate more rapidly while those further out rotate more slowly than the sun
  - First noticed in the study or proper motions
  - Explained by J Oort



Galactic Rotation cont.

- The Sun
  - is 10-20 pc above the Galactic plane
  - and its orbit is not circular
- To compensate for this we define a lsr (local standard of rest)
  - This is the average motion of stars near the sun

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



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

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

- If we are near the Sun (d << R)
  - R R_0 - d sin(l)
  - Then $$V_r = R_0 \sin(l)\left(\frac{V}{R} - \frac{V_0}{R_0}\right)$$

becomes

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

$$d \sin(2l)\left[-\frac{R}{2}\left(\frac{V}{R}\right)'\right]_{R_0} \equiv d\, A \sin(2l)$$

Where A=14.8 km/s/kpc

- We can do the same for proper motions

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

Again close to the sun

$$R \approx R_0 - d\cos(l)$$

$$V_t = R_0 \cos(l)\left(\frac{V}{R} - \frac{V_0}{R_0}\right) - V_0 \frac{d}{R}$$

$$\approx d\sin(2l)\left[-\frac{R}{2}\left(\frac{V}{R}\right)'\right]_{R_0} - \frac{d}{2}\left[\frac{1}{R}(RV)'\right]_{R_0}$$

$$\equiv d\,(A\cos(2l) + B)$$

B = -12.4 km/s/kpc

A & B are called Oort Constants

Oort's constants

- What do they tell us about the Galaxy?
- A measures the local shear
- B measures the local vorticity
- $A – B = V_0/R_0$
  - IF we know R_0 then we can determine V_0
- $\rho_{local} = (B^2 - A^2)/2\pi G$

Sin(l)	+	+	-	-
$V/R - V_0/R_0$	-	+	+	-

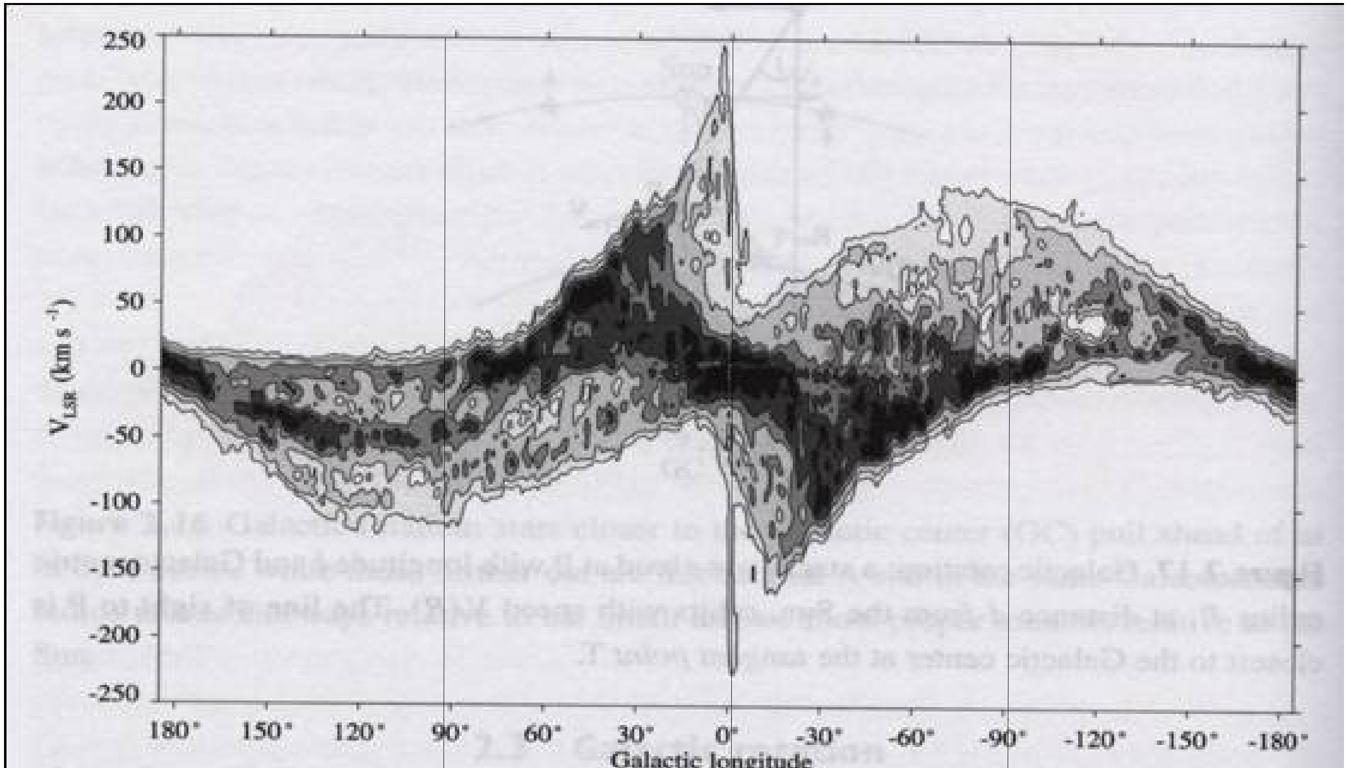


Figure 2.18 In the plane of the disk, the intensity of 21 cm emission from neutral hydrogen gas moving toward or away from us with velocity V_{LSR}, measured relative to the local standard of rest – D. Hartmann, W. Burton.

2nd 1st 4th 3rd Quadrant

- Measuring the velocity at the tangent point works in the inner Galaxy (out to the solar radius)
- Outside R_0 we need to use other methods
  - Spectroscopic parallax for young stars
  - Emission lines from HII regions
  - Emission lines from active stars
- This method shows large variations in V_r and the error bars are much larger than for the data in the inner Galaxy
- Results are the V(r) does not fall and may even rise at radii larger than R_{sun}.

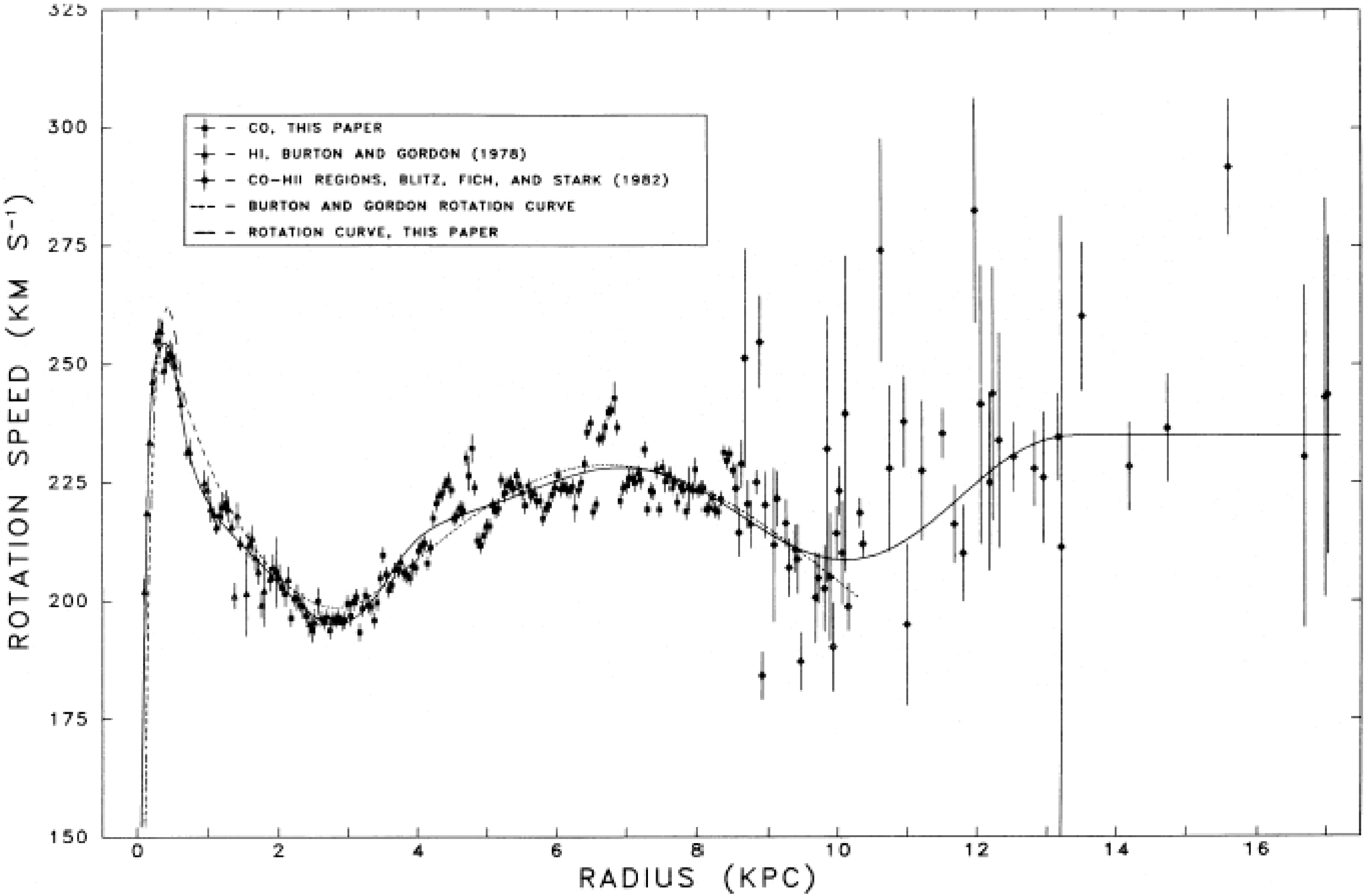


FIG. 3.—Plots of the rotation speed versus galactocentric radius. The solid lines correspond to the polynomials, and the dashed lines are the BG rotation curve. (*upper panel*)(R_0, θ_0) = (10 kpc, 220 km s^{-1}); (*lower panel*) (8.5 kpc, 220 km s^{-1}).

Clemens et al. 1985 ApJ 295 422

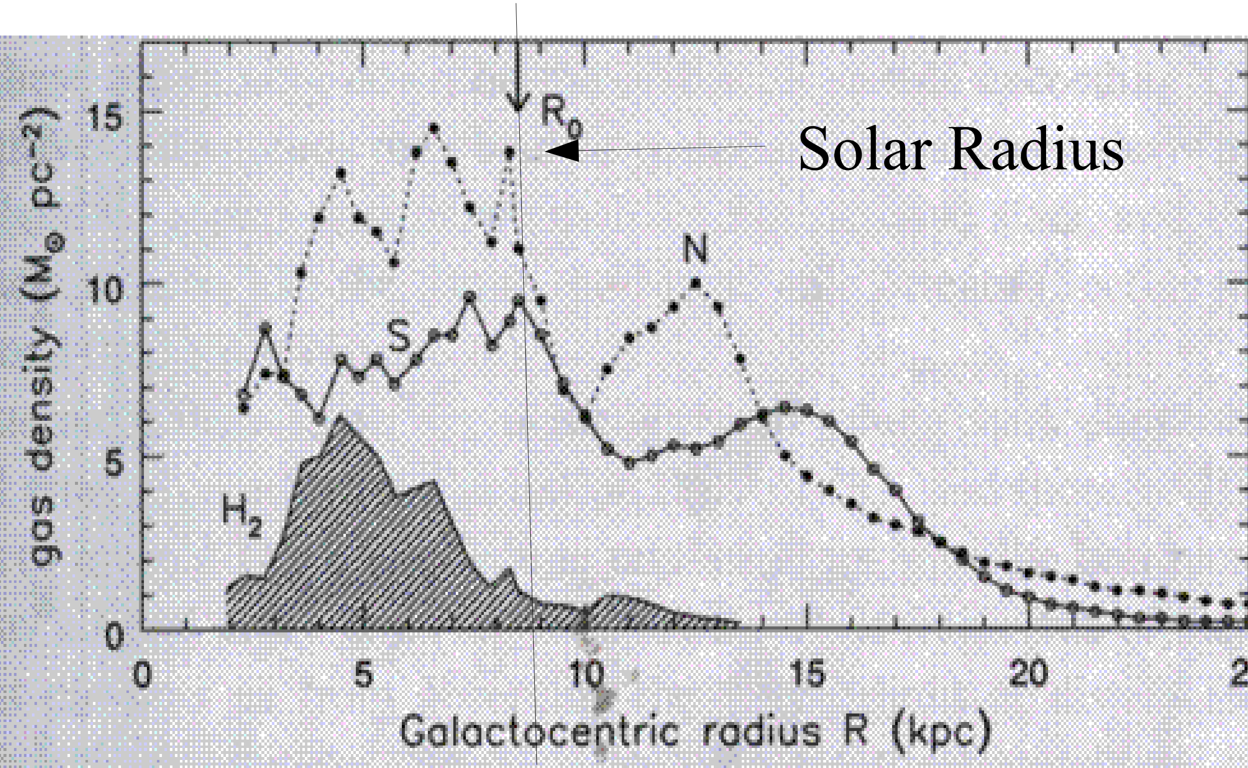
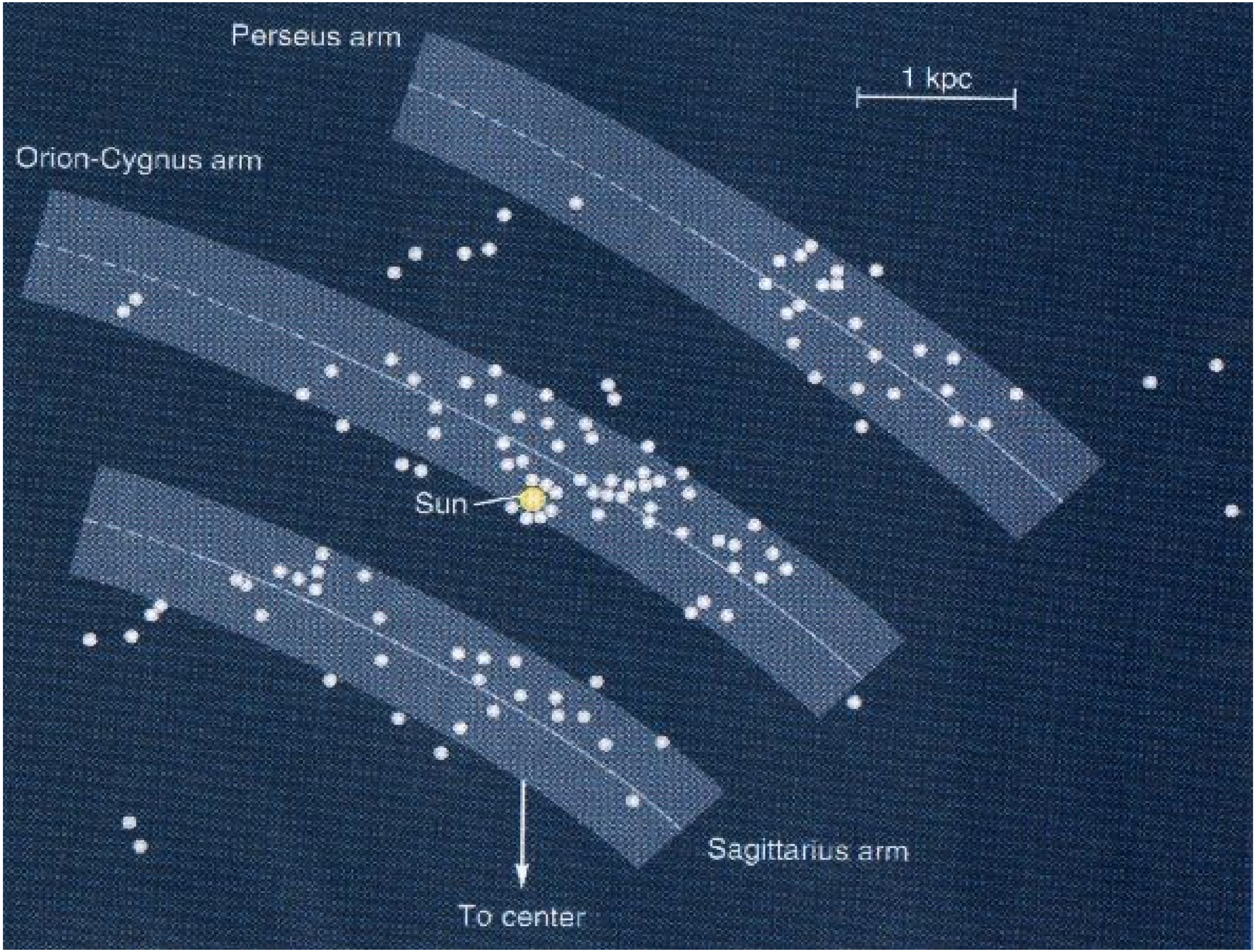


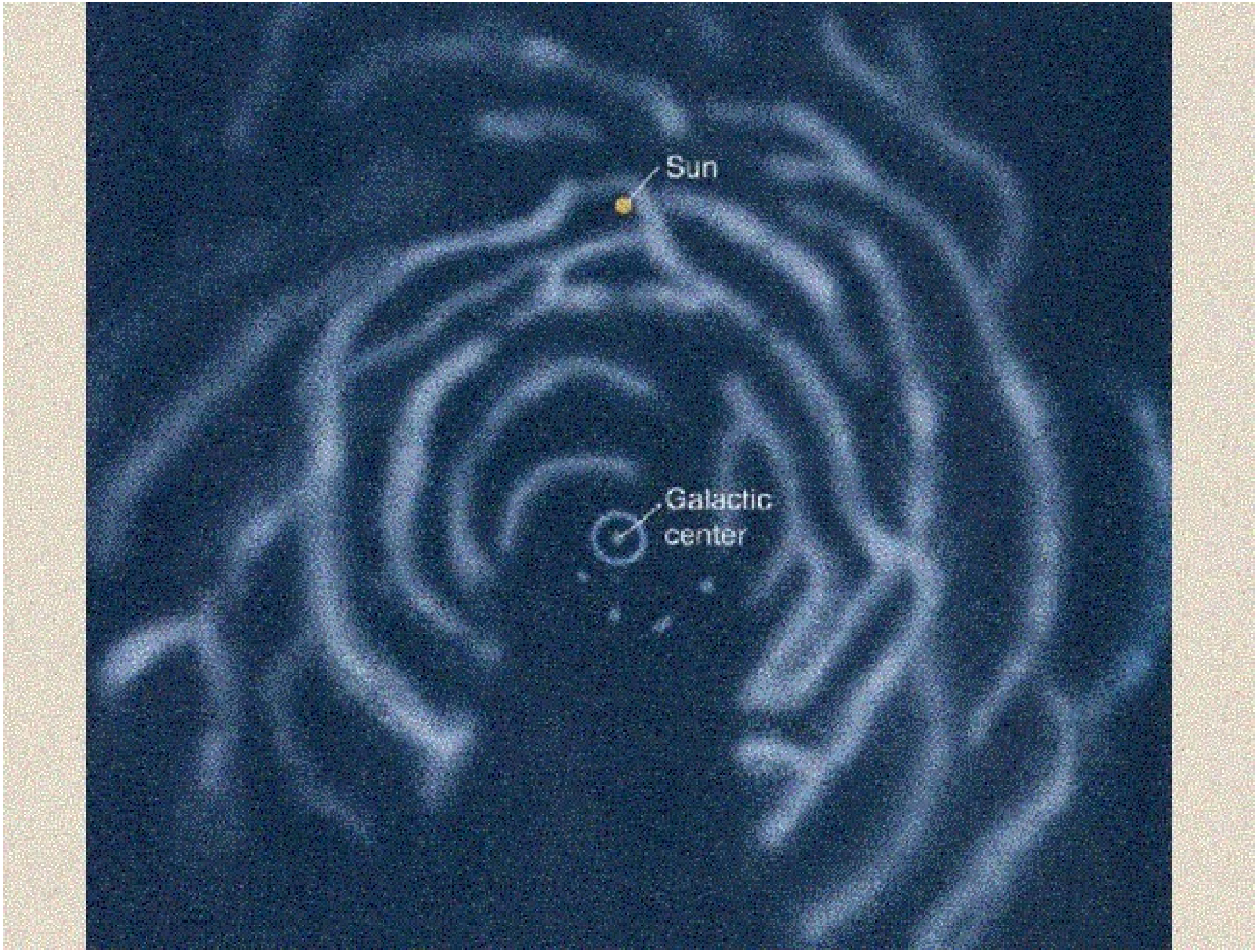
Figure 2.20 Surface density of neutral hydrogen, as estimated separately for the northern ($0 < l < 180°$; filled dots) and southern ($180° < l < 360°$; open circles) half of the Galaxy. Within the solar circle, the density is sensitive to corrections for optical thickness; outside, it depends on what 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.

Once you have the rotation curve, you can go back to observed gas distribution and build maps of the Galactic gas distribution.

Can do this for both HI and molecular gas – they are different (but note that molecular lines are usually optically thick so we can't measure all of it)


Perseus arm
1 kpc
Orion-Cygnus arm
Sun
Sagittarius arm
To center

Schematic view of the Milky Way



Lots of high latitude gas, arcs, bubbles etc.

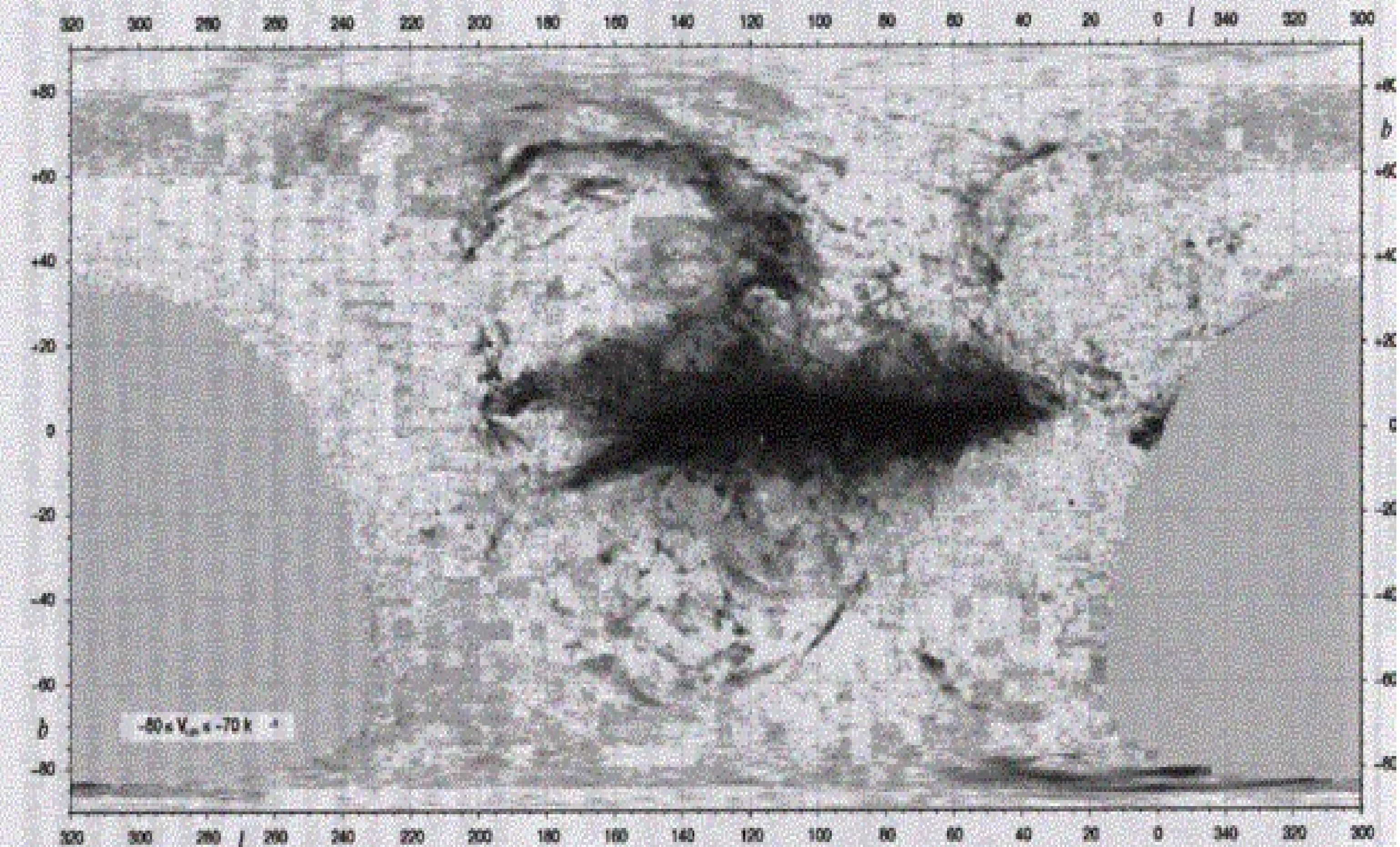
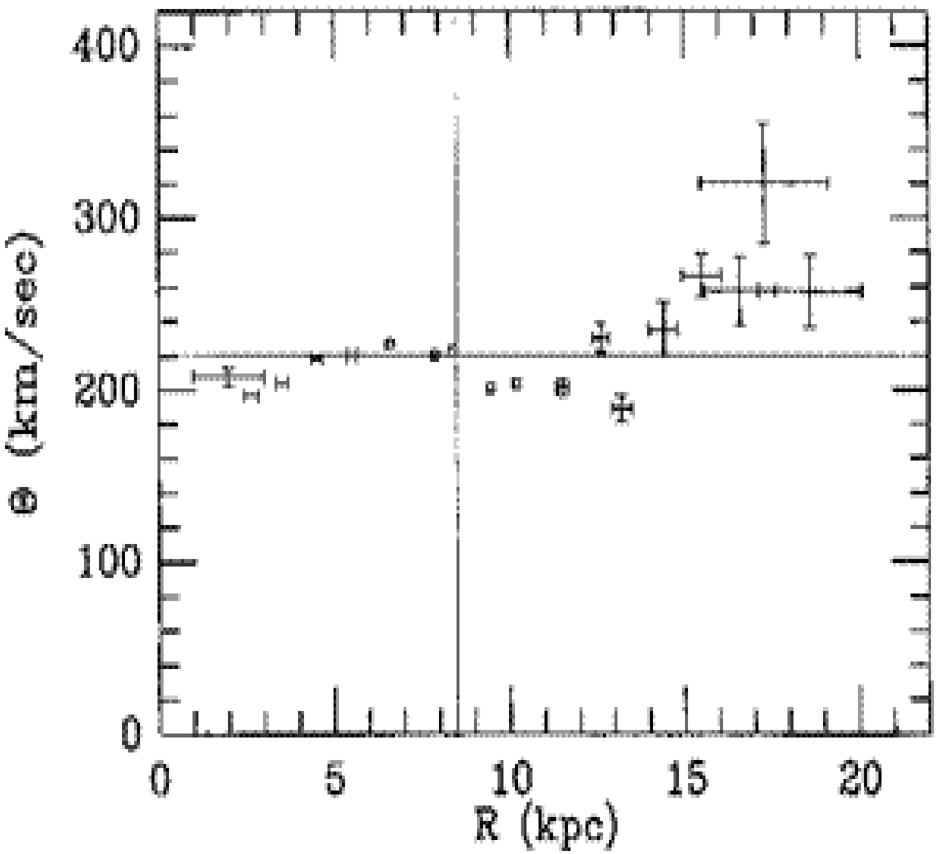
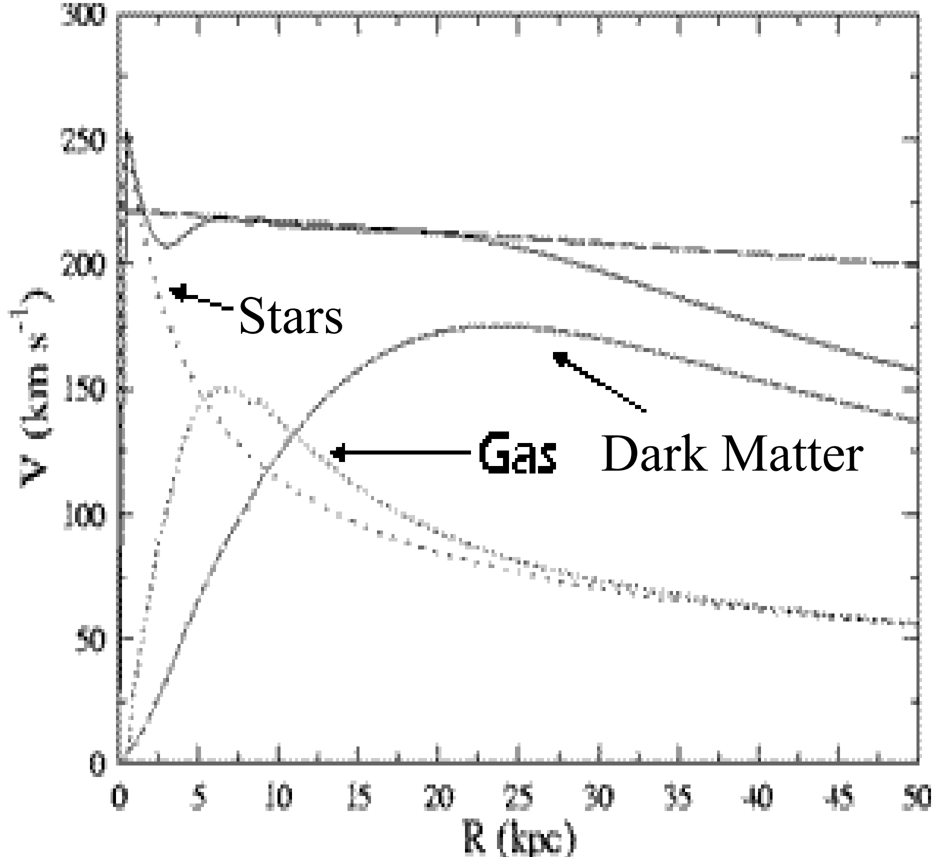


Figure 2.21 Neutral hydrogen at velocities $-80\,\mathrm{km\,s^{-1}} < V_r < -70\,\mathrm{km\,s^{-1}}$; note the high-latitude streamers of gas. Empty areas of the plot could not be ob-served from the telescope in Dwingeloo (Netherlands) – D. Hartmann, W. Burton.





The mass from the stars and gas are not enough to reproduce the rotation curve of the Galaxy.

- Mass must increase as r^1 (linearly)
- Gas and stellar mass decrease after R_0

What is Dark Matter?

- Many candidates for dark matter.
  - Dark Baryons
    - Brown dwarfs?
    - MaCHO's (Massive Compact Halo Objects)
    - Astronomer sized rocks?
    - Black Holes?
  - Non-baryonic
    - WIMPS (Weakly Interacting Massive Particles)