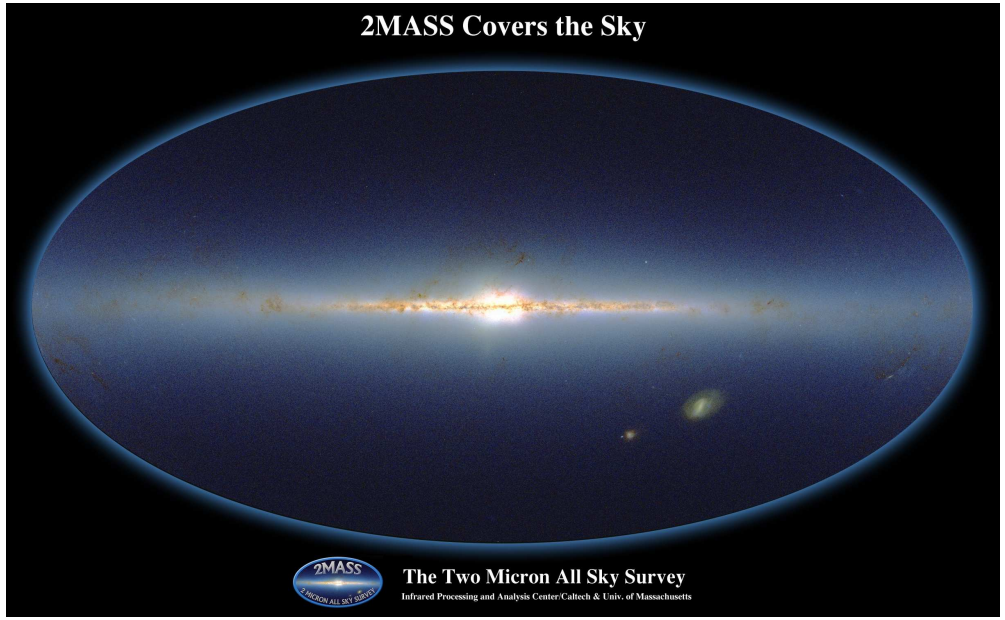
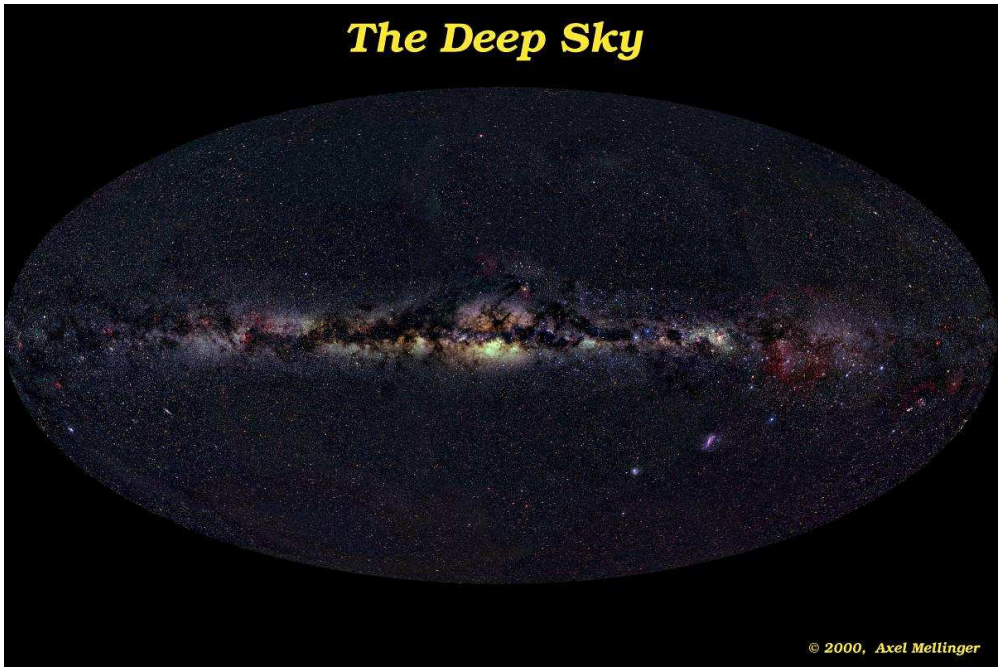
Morphology of the Galaxy



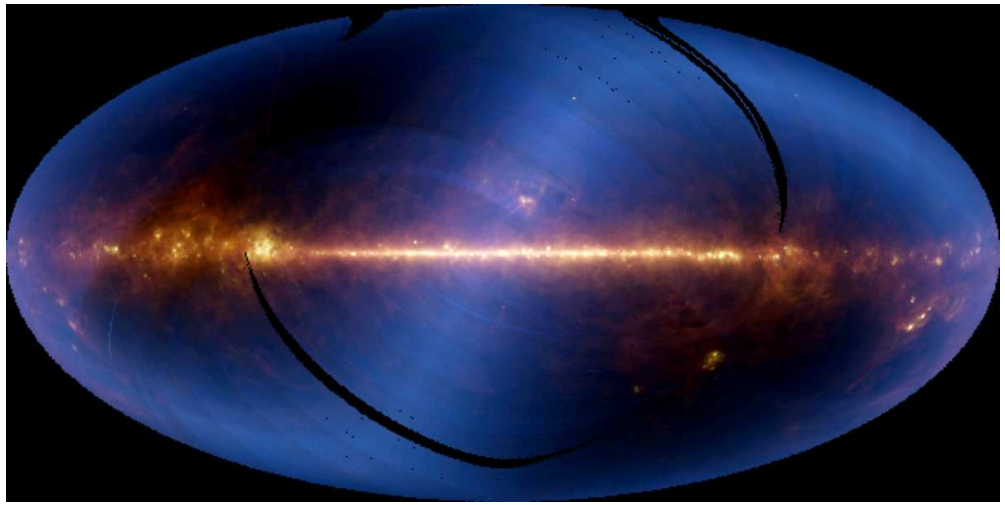
Infra red: Dust becomes transparent!

2MASS: 3 IR Bands: J (1.25 μm), H (1.65 μm), K_s (2.17μm)

Milky Way in Near Infra Red

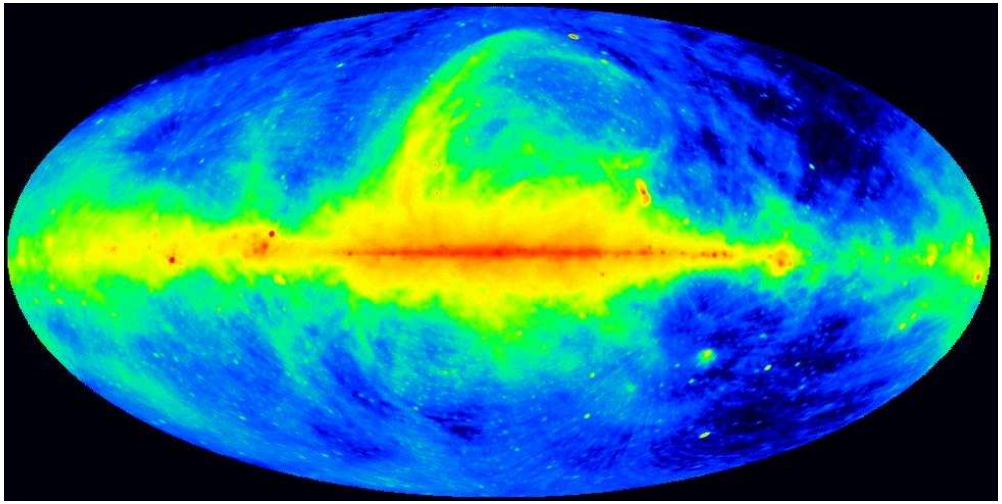


Milky Way in Optical



Milky Way in far Infra Red

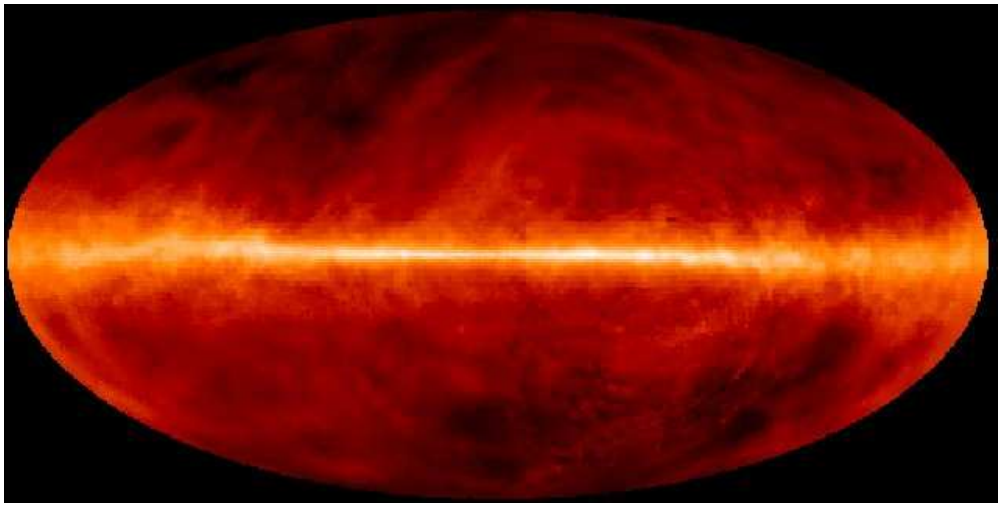
IRAS: 3 IR Bands: blue (12 μm), green (60 μm), red (100 μm)



G.T. Haslam et al., MPI für Radioastronomie 1982

Milky Way in radio ($\lambda = 73\,\mathrm{cm}$, $\nu = 408\,\mathrm{MHz}$)

Continuum radiation (bremsstrahlung, synchrotron radiation)



J. Dickey/F. Lockman/SkyView

Distribution of H I ($\lambda = 21\,\mathrm{cm}$)

Introduction

From the available maps the Galaxy looks like a spiral galaxy.

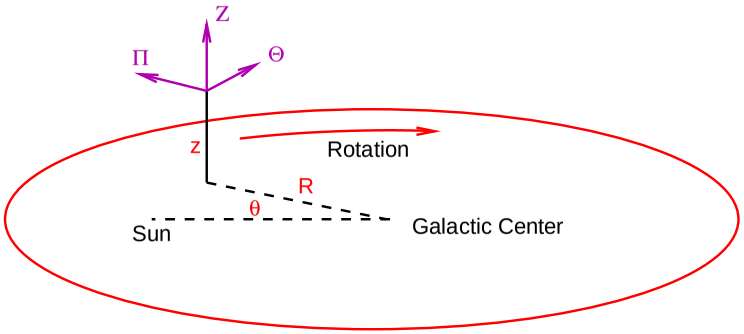
$\Longrightarrow$ How can we determine the structure of the Galaxy in more detail?

Derivation of Galaxy structure is somewhat complicated since we are sitting in it and since the solar system participates with the motion of the Galaxy.

$\Longrightarrow$

1. Galactic Rotation Curve
2. Distribution of gas
3. Evidence for spiral arms

Local Standard of Rest



after Carroll & Ostlie (Fig. 22.21)

Introduce cylindrical coordinate system R, θ, z

$\Longrightarrow$ Velocity components of a star in a cartesian coordinate system:

$$\Pi = \frac{dR}{dt} \qquad \Theta = R\frac{d\theta}{dt} \qquad Z = \frac{dz}{dt} \tag{19.1}$$

Local Standard of Rest

All observations of Galaxy are made from position of Sun.

But Sun moves through space

$\Longrightarrow$ define a *local* coordinate system centered on Sun, which moves on a circular orbit around the center of the Galaxy: Local Standard of Rest (LSR)

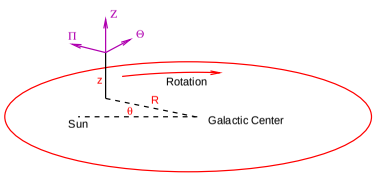
By definition, velocity components of the LSR are:

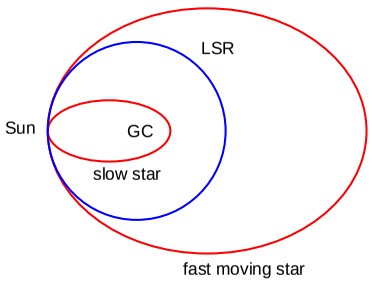
$$\Pi_{\text{LSR}} = 0 \qquad \Theta_{\text{LSR}} =: \Theta_0 \qquad Z = 0 \tag{19.2}$$

Therefore, after measuring motion with respect to LSR, we can convert to Galactic system provided we know Θ_0.

Note that Sun *moves with respect to LSR*!

Motion of the Sun





Velocity of stars relative to LSR: peculiar motion. *Velocity components:*

$$\begin{aligned} u &= \Pi - \Pi_{\text{LSR}} = \Pi \\ v &= \Theta - \Theta_{\text{LSR}} = \Theta - \Theta_0 \\ w &= Z - Z_{\text{LSR}} = Z \end{aligned} \tag{19.3}$$

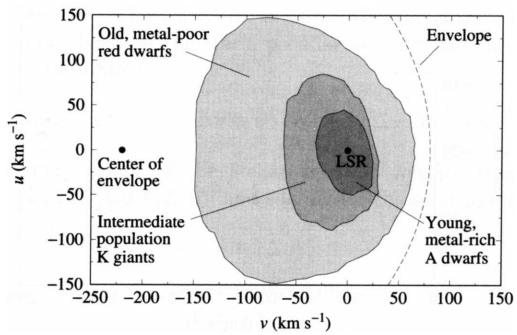
Now look at average u, v, w of stars in solar neighborhood:

- motion in Π and Z should average to zero: $\langle u \rangle = 0$, $\langle w \rangle = 0$, because of symmetry,
- $\langle v \rangle < 0$ because of elliptical motion of stars around Galactic center. Since there are more stars towards GC, more stars move slower than LSR.

From this one can deduce Sun's peculiar velocity:

$$u_\odot = -9\,\text{km}\,\text{s}^{-1}, \quad v_\odot = 12\,\text{km}\,\text{s}^{-1}, \quad w_\odot = 7\,\text{km}\,\text{s}^{-1} \tag{19.4}$$

Motion of the Sun



Carroll & Ostlie (Fig. 22.23)

The distribution objects in u-v-plane ("velocity ellipsoid") depends on type of object.

velocity–metallicity relation: The oldest objects in Galaxy, which have lowest metallicity, have the largest velocity dispersion.

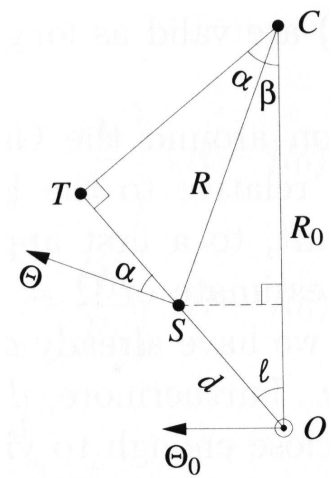
Velocity ellipsoids are asymmetric, oldest objects centered on $v \sim -220\,\text{km}\,\text{s}^{-1}$.

Assumption: these objects do not participate in Galactic rotation

The orbital speed of the LSR is 220 km s^{-1}.

Confirmed by looking at motion with respect to other galaxies.

Galaxy Rotation Curve



Carroll & Ostlie (Fig. 22.24)

To determine rotation of Galaxy ($= \Theta(R)$), our observables are the radial velocities and the transversal velocities of a star S:

$$v_{\text{r}} = \Theta \cos\alpha - \Theta_0 \sin\ell = \Omega R \cos\alpha - \Omega_0 R_0 \sin\ell \tag{19.5}$$

$$v_{\text{t}} = \Theta \sin\alpha - \Theta_0 \cos\ell = \Omega R \sin\alpha - \Omega_0 R_0 \sin\ell \tag{19.6}$$

where ℓ: galactic longitude, $\Omega = \Theta/R$: angular velocity

But from geometry of $\triangle OTC$:

$$R \cos\alpha = R_0 \sin\ell \tag{19.7}$$

$$R \sin\alpha = R_0 \cos\ell - d \tag{19.8}$$

such that

$$v_{\text{r}} = (\Omega - \Omega_0) R_0 \sin\ell \tag{19.9}$$

$$v_{\text{t}} = (\Omega - \Omega_0) R_0 \cos\ell - \Omega d \tag{19.10}$$

$\Longrightarrow$ We can determine Ω from v_{r}!

Gas Distribution

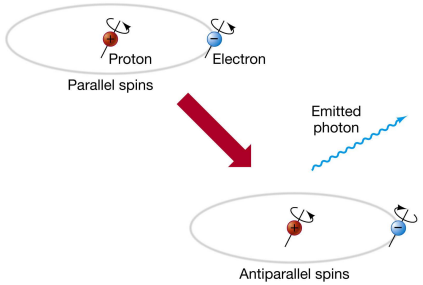
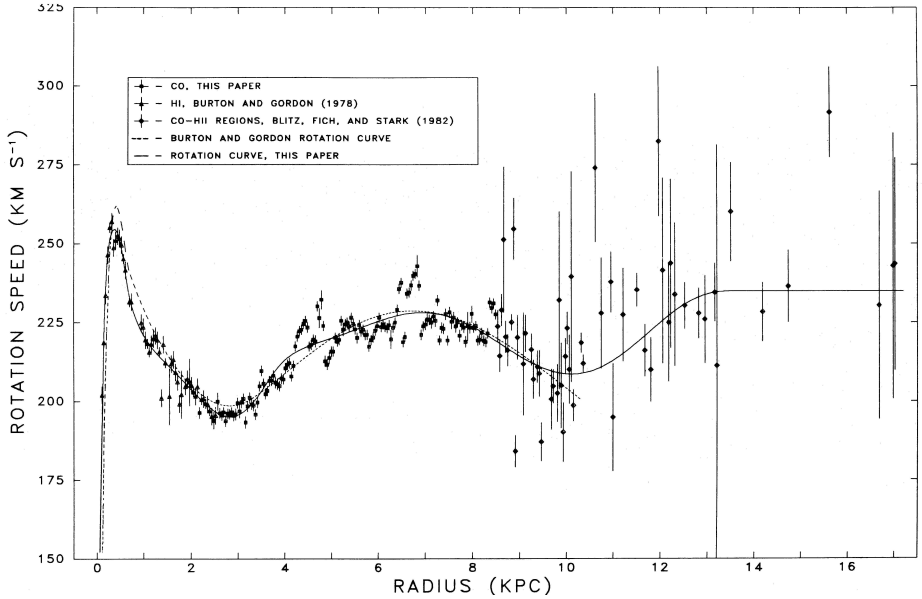


Image: 2005, Pearson Prentice Hall, Inc.

- Spins of electron and proton may be parallel ($F = 1$) or antiparallel ($F = 0$) ("hyperfine levels"); energy difference of $\Delta E \sim 6 \times 10^{-6}$ eV, corresponding to $\lambda = 21$ cm or $\nu = 1.4$ GHz.
- $F = 1$ is metastable, i.e., long life time (10^7 years); transition to $F = 0$ *dipole forbidden* in quantum mechanics, transition rate 10^{-6} smaller than for permitted transitions.
- Laboratory: $F = 1$ state is depopulated by collisions; no line is seen.
- ISM: low densities, i.e., no collisions; radiative transitions possible.

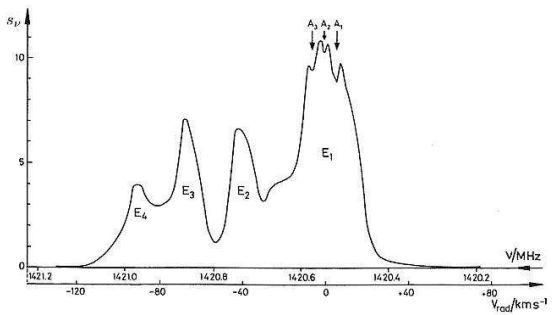
Because of the ubiquity of hydrogen, 21 cm line traces gas extremely well. Self-absorption of the line is extremely unlikely $\Longrightarrow$ line visible from everywhere except for the most dense regions.

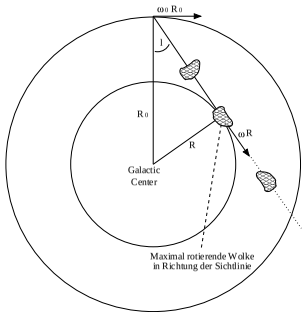


Clemens (1985, Fig. 3)

The rotation curve of the galaxy is approximately flat.

Gas Distribution





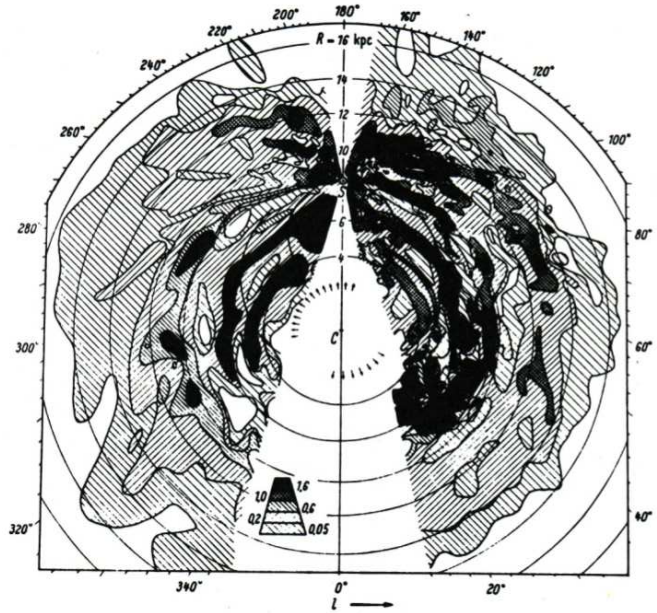
Sketch of a typical H I emission line profile. Note: v-axis has wrong sign!

In general multiple hydrogen clouds along the line of sight. Differential rotation $\Rightarrow$ Differential Doppler shift, allows to obtain $\Omega(R)$ (note: maximum v_r at $R = R_0 \sin \ell$!).

Overall: Probe of ISM structure and dynamics!

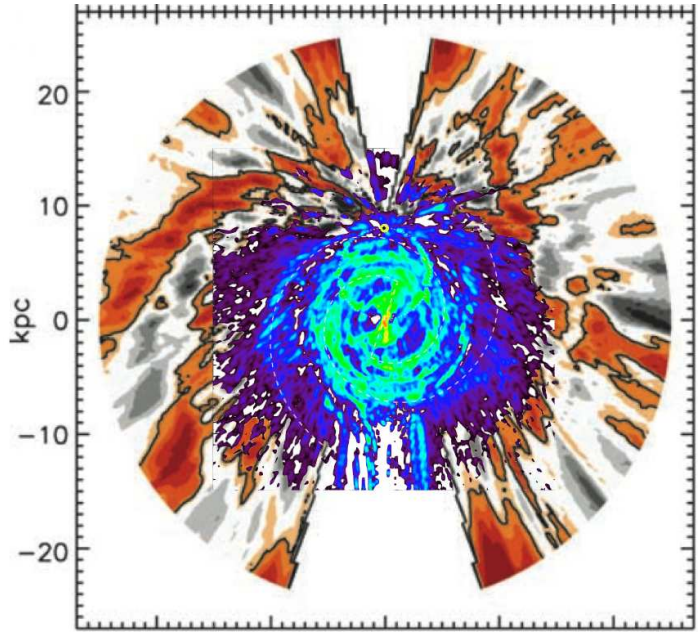
Integration over the full profile gives the column density of neutral hydrogen in this direction. Typical values: 10^{18} cm^{-2} (at large gal. latitudes) to 10^{22} cm^{-2} (in the gal. plane).

State of the art is the Leiden-Argentine-Bonn Survey (Kalberla et al., 2005).



from Englmaier, Pohl, Bissanz (2008, Fig. 1)

Oort (1958): First map of H distribution in Galaxy: structure!

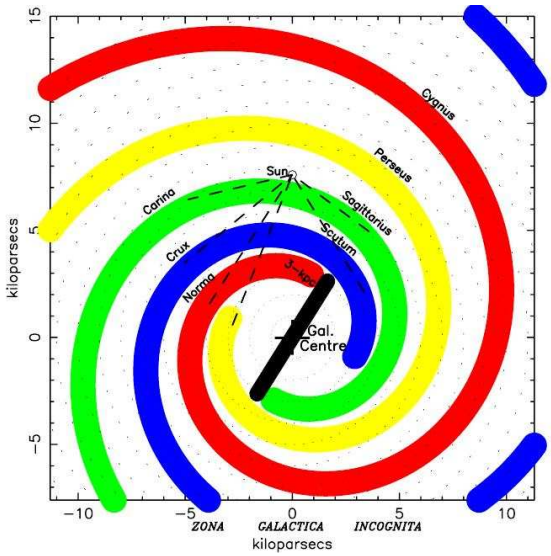


from Englmaier, Pohl, Bissanz (2008, Fig. 2; Sun is yellow dot)

Distribution of CO and H gas shows clearly the spiral structure.

19–18

Evidence for Spiral Arms

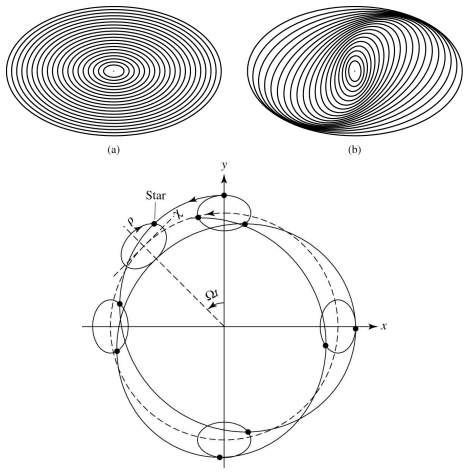


The spiral arm structure of Galaxy is now rather well understood

Vallee (2008)

19–19

Spiral Arms

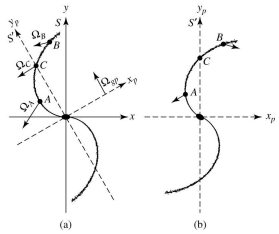


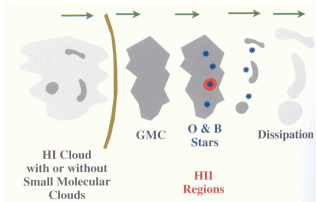
Carroll & Ostlie

Spiral structure and density waves:
Stars do not move on circles but on “nested ovals”
If each oval is rotated relative to the orbit immediately interior to it: spiral density wave
First order approximation: combination of a retrograde motion about an epicycle and a prograde circular orbit of the epicycle centre

19–20

Spiral Arms





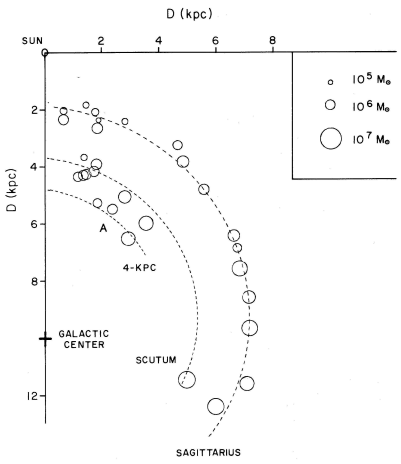
Carroll & Ostlie

- Quasistatic density wave moving with a globular angular pattern speed $\Omega_{\rm gp}$
- Star A: $\Omega_{\rm gp} > \Omega_{\rm gp}$
- Star B: $\Omega_{\rm gp} < \Omega_{\rm gp}$
- Star C: $\Omega_{\rm gp} = \Omega_{\rm gp}$ (corotating)

Star formation induced by density wave:

- A cloud of gas passes through a density wave
- compression induces collapse
- stars of all masses form
- massive stars dissipate the cloud by their strong UV radiation

Spiral Arms



Dame et al. (1986, Fig. 9)

Star formation induced by density wave:

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