Other results from CO and H I observations of the Milky Way
- Spiral structure in the Galaxy
- The 5 kpc molecular ring
- Noncircular motions
- The bar at the center of the Galaxy

Other normal spiral galaxies
- Shapes and sizes, Hubble sequence
- Evidence for galaxy interactions

Image: M83, from the FORS1 camera on VLT Antu (ESO)
Molecular- and atomic-line surveys of the Galaxy

Once the rotation curve is established, one can work out the three-dimensional structure of the Galaxy.

A big job: the Galaxy extends over a 10 degree by 360 degree solid angle, and over almost 600 km/s in radial velocity, and the details important for Galactic structure studies are as small as 1 arcminute and a few km/s.

Thus it’s not done completely in that detail yet, but we’re getting there.

- 1’ resolution Galactic plane H I 21 cm survey under way at DRAO (British Columbia)
- 1’ resolution Galactic plane CO 2.6 mm survey at FCRAO (Massachusetts)
Columbia U. CO survey (Dame, Hartmann and Thaddeus)
Molecular cloud complexes in the Galactic plane
The three-dimensional structure of the ISM in the inner Galaxy: a spiral pattern

With detailed images and line velocities with respect to the LSR, the distance ambiguity can be resolved fairly well:

- association or lack thereof with visible-wavelength emission: relatively unobscured clouds tend to be closer to us.
- cloud size: bigger ones (in angular size) tend to be nearer by.
- height above Galactic plane: clouds that appear higher would be closer to us.

Tangent lines show spiral arms

Result: spiral structure is detected in the inner (and outer) Galaxy.
Circular motions
Longitude-velocity diagram of a uniformly-rotating ring.

For a distant observer the velocity component along the line of sight only depends only on \( \sin \ell \), line of sight component is the same on front and back sides of the ring.
Noncircular motions (continued)

Observer

Longitude-velocity diagram of an expanding ring.
Noncircular motions (continued)

Observer

Longitude-velocity diagram of a rotating, expanding ring.
Noncircular motions (continued)

Observer

Longitude-velocity diagram of an ellipse.

Non-zero line of sight velocities at $l=0$

Longitude-velocity diagram of an ellipse.
Motions in the inner Galaxy

The “noncircular” motions are best described as the superposition of a complicated set of rotating, expanding/contracting orbits, similar to those shown.

- The origin of these orbits is best described by a bar-shaped inner stellar distribution.
- This also would explain the 3-4 kpc ring, as a resonant orbit in the rotating barred gravitational potential.
- Many features also due to spiral arms!
Velocity fields of galaxies
Barred galaxy velocity field, NGC 1365

Rutger’s Fabry Perot
HI in Circinus Galaxy

probably a warp

ATCA HI image by B. Koribalski (ATNF, CSIRO), K. Jones, M. Elmouttie (University of Queensland) and R. Haynes (ATNF, CSIRO).
Ringed barred galaxy NGC1808
Bärbel Koribalski – HI observations and 2mass image
Asymmetric bulge

Left hand side appears larger because that is the near side of the bar/bulge.
X-shaped bulge
M95 (NGC 3351), an SBb galaxy

Photograph by David Malin (AAO), with the Anglo-Australian Telescope (3.8 m).

This is probably what the Milky Way looks like from a point high above its north pole. The position the Sun would have is marked with a cross.
Galaxies are classified by shape into the so-called Hubble types, listed here in this “tuning-fork” diagram. Different spiral galaxy types are distinguished by the shapes of their disks and bulges, as shown in the following.
M74 (NGC 628), an Sc galaxy

Color composite image from the Gemini North observatory 8 m telescope. Note the relatively small bulge, very strong spiral structure, very blue color of the spiral arms, and the dust lanes on the trailing edges of the arms.
M33 (NGC 598), an Sc galaxy

Photograph by David Malin (AAO), with the Isaac Newton Telescope.

Note the diffuse spiral structure, compared to M74. M74 is a grand design spiral galaxy; M33 is a flocculent spiral galaxy.
NGC 1288, an Sb galaxy

BVI color composite image from the FORS1 camera on the 8.2 m VLT Antu telescope (European Southern Observatory). Sb galaxies are distinguished from Scs by less-open spiral structure and by more prominent bulge.
M65 (NGC 3623), an Sa galaxy

Photograph by David Malin (AAO), with the Anglo-Australian Telescope (3.8 m).

Sa galaxies have even tighter spiral patterns and yet more prominent bulges.
Bulge/disk size in edge-on spiral galaxies
(False-color 1.2, 1.6, 2.2 µm images from 2MASS)

NGC 7814: Sa
NGC 891: Sb
NGC 5907: Sc
NGC 1365, an SBc galaxy

*BRI* color-composite image with the FORS1 camera, on the VLT Antu 8.2m telescope (European Southern Observatory).

Note that it has at least two concentric bars, oriented in different directions.
Nearby low luminosity elliptical galaxy M32

Very high density core

Million stars per pc$^3$

$10^8$ solar mass black hole in center

**Credit:** Thomas M. Brown (GFSC) et al., NASA
Spiral galaxy rotation curves

Solid-body inner part, then it’s flat, as far out as gas can be detected.

Dark matter?

Figure: Chaisson and McMillan, *Astronomy Today*. 
NGC 2992/3 Observations and simulations

Credit Max-Planck institut Garching
Simulations of galaxy interactions and mergers
credit MPA-Garching
Evidence for galaxy interactions

NGC 2787

Hoag’s Object

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC02-21
Shell Galaxies

Shell Galaxies in Pisces
Stephen Leshin APOD
Galaxy environments range from

- Field
- Small groups
- Large clusters
One galaxy in front of another:
Overlapping galaxies
Overlapping galaxies which are also interacting tidally

Galaxies NGC 2207 and IC 2163
Galaxies which are under-represented in most surveys

• Compact galaxies  (for example as recently discovered in Fornax and Coma clusters from redshift surveys)
• Low surface brightness galaxies (examples shown below)

UGC 1230  
credit U Oregon

UGC 6614
Molecular gas in Galaxies

OVRO CO map of M51 overlaid on an HST image, from Aalto et al. 1999

In general there is more molecular gas in the centers of galaxies, and more atomic in the outskirts
Things which are correlated with Hubble type

- Gas mass fraction
- Color - function of age and metallicity
- Star formation rate
- Bulge
- Mass of central black hole
- Strength and number of spiral arms
- Environment
- Type of AGN which might exist in nucleus
- Disk surface brightness
- Symmetry
- Bar fraction