

Lecture Seven:

The Milky Way: Gas

<http://www.astro.rug.nl/~etolstoy/pog14>

Gas in the Milky Way

Between the stars in the disc of the Milky Way there is gas, which is the stuff from which the stars were originally made, and to which stars return heavy elements from their nuclear burning processes. Almost all the gas in the Milky Way lies in the disc, although the mass of gas is only 10% of the mass in stars.

Gas gives a galaxy its distinctive properties, without gas the Milky Way would be an S0 galaxy, not a spiral, as the disc would have no young stars and no spiral pattern.

Only half the starlight from the Milky Way escapes the galaxy, dusty interstellar gas absorbs the rest.

7th May 2014

Sparke & Gallagher, chapter 1,2

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Gas in the Milky Way

Like the stars, the gas in the Milky Way is subject to gravity, which ultimately causes the densest gas to collapse and form new stars.

However, unlike stars, the interstellar gas is subject to additional forces like gas pressure, magnetic forces, and the pressure caused by Cosmic Rays. The gas is heated and ionised by stellar radiation; it is shocked and set into motion by fast stellar winds, violent supernovae explosions and passage through the spiral arms - it is a complex environment!

Unlike stars, gas does not come in standard units of size. The mass of a clump of gas is not related to its temperature, or any other quantity we can measure independent of distance.

So the distances to gas clouds are very uncertain, except for very unusual cases where we know that the gas surrounds a star.

When we see absorption lines from the gas in the spectra of stars, then we know the gas is in front of the star.

From gas in circular orbits in the Milky Way disc we can determine kinematic distances. We can measure the radial velocity of the gas in all directions, and thus build up a picture of how the gas is distributed in the disc of the Milky Way.

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Gas in the Milky Way

When all radiation reaches us without being absorbed (optically thin emission), the mass of gas moving with a particular velocity is proportional to the intensity of the radiation.

Visible light is absorbed by interstellar dust, whereas radio waves can travel through.

But sometimes in a large disc of gas we can look through enough material that the radio waves from distant gas are partially absorbed by gas closer to us (optically thick emission). HI is optically thick in the inner parts of the Milky Way, for example.

Dense cool clouds are often traced by molecular emission, at millimetre wavelengths, of ^{12}CO , which are nearly always optically thick, much molecular gas is thus hidden from view.

The most common molecule is H_2 , but because it is a symmetric molecule there are no strong emission lines, making it very hard to detect directly. The next most abundant molecule is CO (there is one CO molecule for every 10^4 of H_2).

Interstellar gas is in motion on large and small scales. Like stars, interstellar gas clouds do not follow exactly circular orbits about the Galactic centre. They also have random motions, typically $\sim 5\text{km/s}$ for molecular clouds, and $8\text{-}10\text{km/s}$ for clouds of HI.

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Neutral atomic hydrogen: HI

Hydrogen is the most abundant element in the Universe and in the interstellar medium (ISM) of the Milky Way.

The cold interstellar gas does not emit radiation at visible wavelength, but at radio wavelengths due to a hyperfine line from two closely spaced energy levels in the ground state of the neutral H atom (HI). An HI atom with the spins aligned will spontaneously flip back to the lower energy, non-aligned, state after sometime.

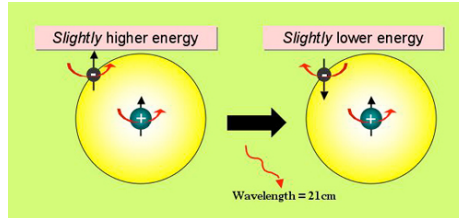
hyperfine transitions are a consequence of coupling between nuclear spin and the magnetic field generated by the orbiting electron.

The frequency of the center of this line is defined from quantum mechanics:

$$\nu_{10} = \frac{8}{3}g_I \left(\frac{m_e}{m_p} \right) \alpha^2 (R_M c) = 1420.406 \text{ MHz}$$

where $g_I \approx 5.58569$ is the nuclear g-factor for a proton, $\alpha \equiv e^2 / (\hbar c) \approx 1/137.036$ is the fine structure constant, and $R_M c$ is the Rydberg frequency

This frequency corresponds to a wavelength, $\lambda \approx 21 \text{ cm}$ and therefore this line is often called "the 21-cm line"



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Neutral atomic hydrogen: HI

The 21-cm line is the result of the magnetic interaction between the electron and proton spins and so is a magnetic dipole transition

The emission coefficient of this magnetic dipole is: $A_{10} = \frac{64\pi^4}{3hc^3} \nu_{10}^3 |\mu_{10}^*|^2$,

where $|\mu_{10}^*|$ is the Bohr magneton, the intrinsic dipole moment of the electron: electrons have spin angular momentum $L = \hbar/2$, classical radius $r_e = e^2 / (m_e c^2)$, and charge e , so

$$|\mu_{10}^*| = \frac{\hbar}{2} \frac{e}{m_e c} \approx 9.27 \times 10^{-21} \text{ erg G}^{-1}$$

Thus the emission coefficient for the 21-cm line is $A_{10} = 2.85 \times 10^{-15} \text{ s}^{-1}$

and therefore its radiative half-life is about

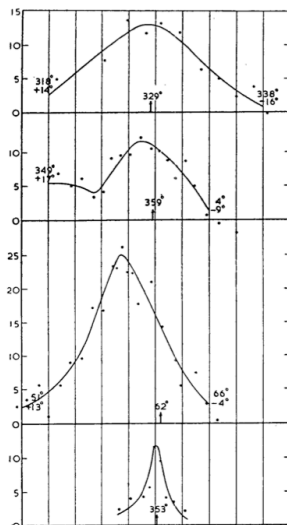
$$\tau_{1/2} = A_{10}^{-1} \approx 3.5 \times 10^{14} \text{ s} \approx 11 \text{ million years}$$

This is really long! But there's a lot of neutral hydrogen out there...

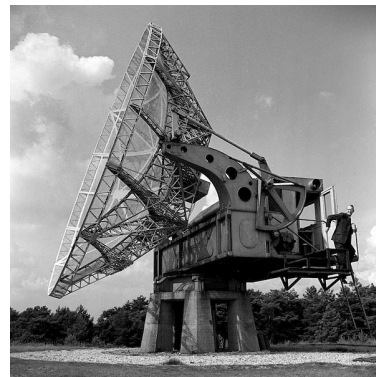
One of the rare occasions in astronomy where a non-terrestrial phenomena was precisely predicted, by Henk van de Hulst in 1944 before it was actually observed, in 1951.

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First Detection of HI



First Dutch Radio Telescope, Kootwijk



Ewen & Purcell 1951, Nature, 168, 356
Muller & Oort 1951, Nature, 168, 357

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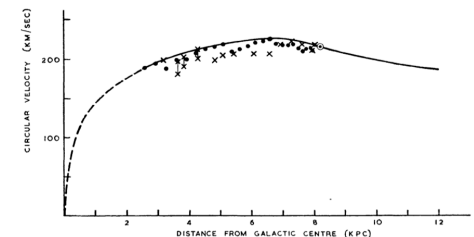
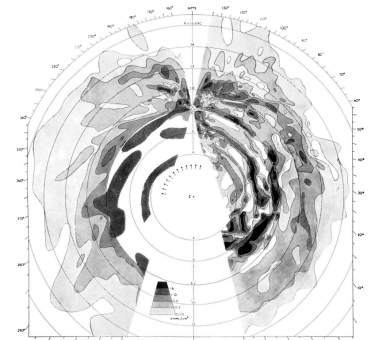
Mapping the Milky Way in HI

By measuring the radial velocity of the 21 cm line and its intensity, we can measure the distance to and amount of HI in the Milky Way

compare the observed frequency of the line with 1420.406 MHz to get the radial velocity:

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} = \frac{\nu_{\text{em}} - \nu_{\text{obs}}}{\nu_{\text{obs}}} \text{ and } v = cz$$

and integrate the observed intensity over frequency to get the column density (N_{HI} in cm^{-2}) of neutral hydrogen

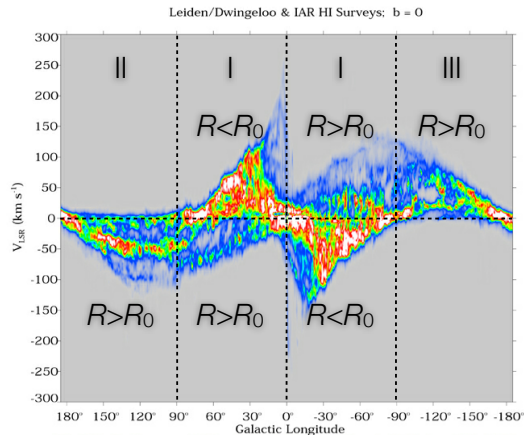


Oort, Kerr & Westerhout 1958 MNRAS, 118, 379

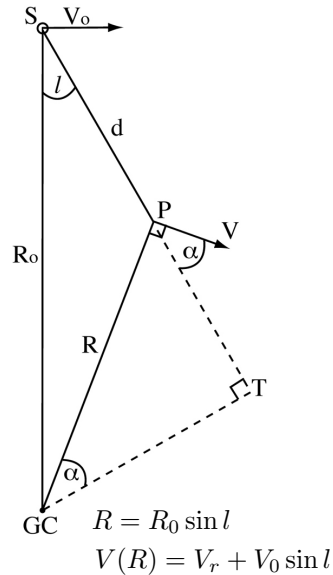
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The Leiden-Argentina-Bonn (LAB) HI Survey

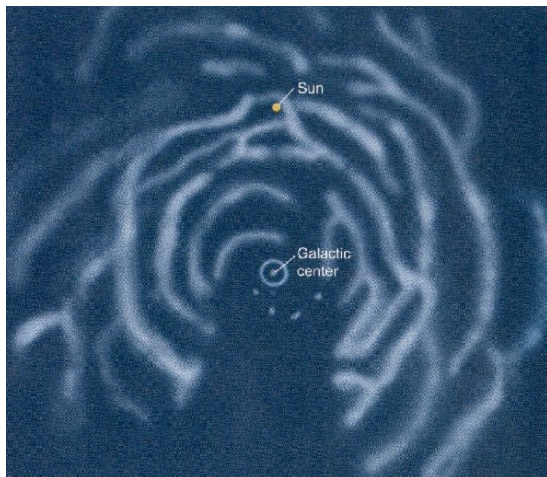
$$V_r = R_0 \sin l \left(\frac{V}{R} - \frac{V_0}{R_0} \right)$$



Kalberla et al. 2005 A&A



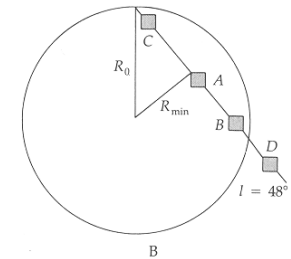
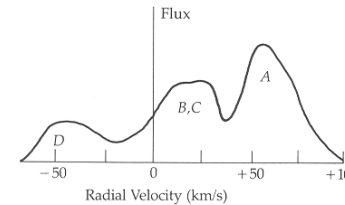
The distribution of HI in the Milky Way



Kinematic distances to gas in the Milky Way

As we look across the MW, we see the HI gas take on a distribution of gas clouds with different radial velocities

These are clouds at different distances with different angular speeds



Cloud A has the highest velocity: it sits at the tangent point along our line of sight, so its radial velocity is maximized

Clouds B & C have different distances but the same velocity: they sit at the same radius from the GC with the same velocity

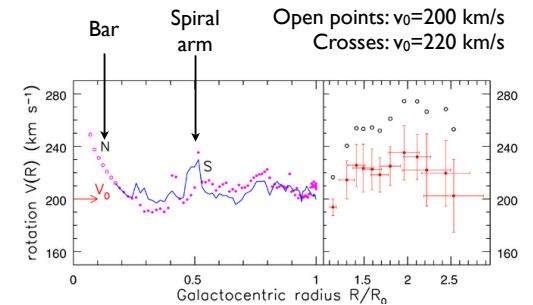
Cloud D is the furthest and has negative velocity because it sits at $R > R_0$

The rotation curve of the Milky Way from HI

By mapping the MW in HI, we can then determine the rotation curve $V(R)$

This only works for circular motion around the Galactic centre: spiral arms and the Galactic bar will disturb the rotation curve by 10–20 km/s or more.

In the outer galaxy, we need to use other tracers, like young stars or their associated hot or cold gas clouds



N: Northern HI ($0^\circ < l < 180^\circ$)
S: Southern HI ($180^\circ < l < 360^\circ$)

The distribution of HI in the Milky Way

The column density of neutral hydrogen gas along some line of sight is defined:

$$N_{\text{HI}} = \int_{\text{los}} n_{\text{HI}} ds$$

where n_{HI} is the number density of neutral hydrogen (HI) atoms

If the optical depth of the cloud, $\tau \ll 1$, then we can measure the column density from the flux emitted by the cloud as

$$N_{\text{HI}} = 1.82 \times 10^{18} \int \left[\frac{T_b(v)}{\text{K}} \right] d \left(\frac{v}{\text{km s}^{-1}} \right) \text{ cm}^{-2}$$

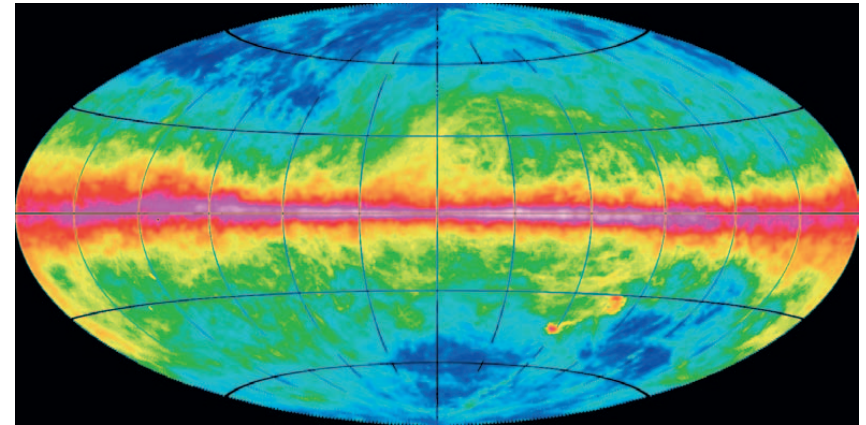
where $T_b(v)$ is the observed 21cm brightness temperature, and the velocity integration extends over the entire HI profile.

$n(\text{HI}) \sim 1 \text{ cm}^{-3}$ in spiral arms and 0.1 cm^{-3} in between
 $T \sim 125 \text{ K}$

$$T_b = \frac{I_\nu c^2}{2k\nu^2}$$

$$h\nu \ll kT$$

The distribution of HI in the Milky Way



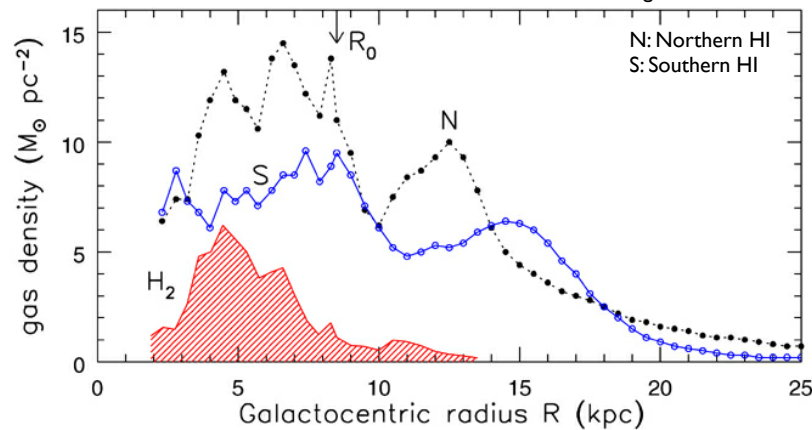
Kalberla et al. (2005): the Leiden-Argentina-Bonn Survey

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The distribution of HI & H₂ in the Milky Way

based on kinematic distances, using CO to trace H₂.



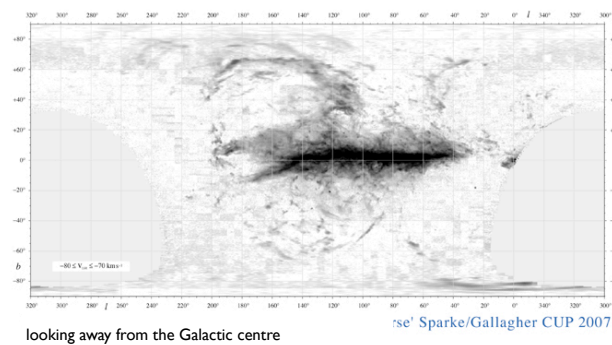
“Spikes” are spiral-arm crossings

$M(\text{HI})_{\text{MW}} \approx 4\text{-}8 \times 10^9 M_\odot$ twice the mass of H₂.

Note that the distribution of HI in the Northern and Southern MW is not the same

almost all H₂ but less than half HI lies within the solar circle
 Molecular gas is piled up in a ring of radius 4 kpc.
 HI disc is thicker than molecular disc.

The distribution of HI in the Milky Way halo



looking away from the Galactic centre

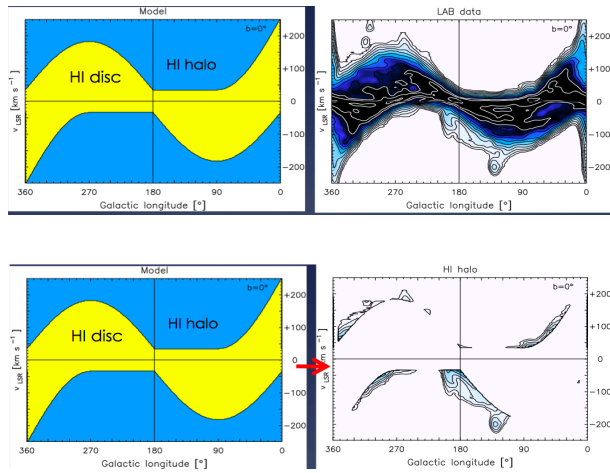
see Sparke/Gallagher CUP 2007

HI can also be found far above the plane of the disc. These are high-velocity clouds of HI that rain down on the disc with velocities approaching 100km/s. Some of this may be disc material which has been thrown up by supernovae or winds from hot massive stars, and now it is falling back. Some are known to come from external systems (e.g., Magellanic Stream).

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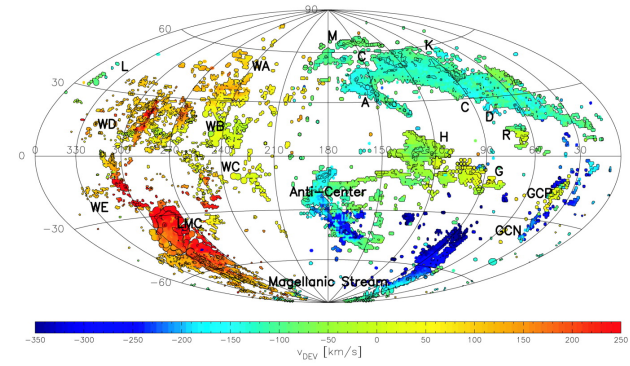
The distribution of HI in the Milky Way halo



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The distribution of HI in the Milky Way halo

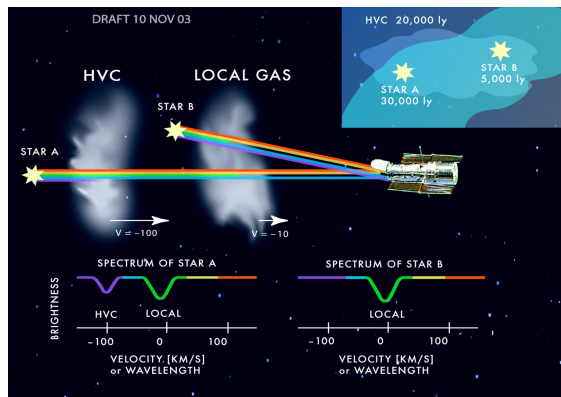
HIGH VELOCITY CLOUDS



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The distribution of HI in the Milky Way halo

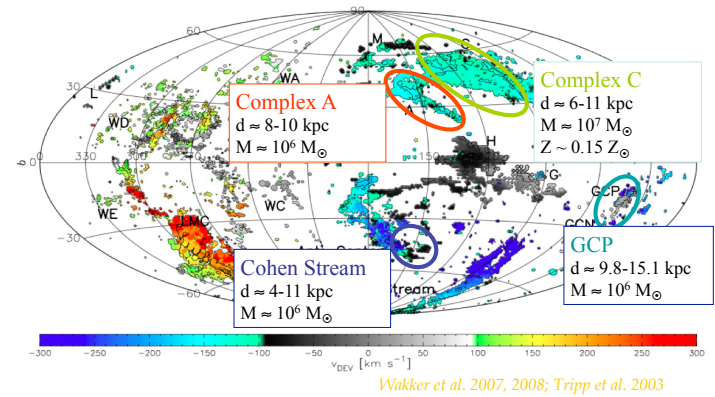
HIGH VELOCITY CLOUDS



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The distribution of HI in the Milky Way halo

HIGH VELOCITY CLOUDS



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Molecular gas in the Milky Way

Molecular hydrogen, H₂, is symmetric and therefore has no permanent electric dipole moment. So despite the fact that H₂ is the most abundant molecule in the Universe, it only radiates when shocked or irradiated to T ≥ 1000 K, while most H₂ is at T ~ 10–100 K.

A polar molecule has a non-zero electric dipole moment and so will radiate due to both rotational and vibrational modes

A rotating molecule has an angular momentum that is quantized in units of \hbar : $L = n\hbar = I\omega$ where I is the moment of inertia of the molecule and ω is its angular frequency of rotation

The energy of the state with rotational quantum level J is

$$E_{\text{rot}} = \frac{J(J+1)\hbar^2}{2I}, \text{ where } J = 0, 1, 2, \dots$$

And only transitions between states J and J ± 1 are permitted: $\Delta J = \pm 1$

The emitted frequency of a transition is then
$$\nu = \frac{\hbar J}{2\pi m r_{\text{eq}}^2}$$

where m is the reduced mass of the molecule and r_{eq} is its equilibrium radius

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Molecular gas in the Milky Way

CO is the second most abundant molecule in the galaxy (after H₂), with J=0-1 and J=1-2 transitions at 2.6 mm and 1.3 mm respectively

The minimum required temperature to excite a molecule is $T_{\text{min}} \sim E_{\text{rot}}/k$

For CO J=0-1 and J=1-2, the excitation temperatures are ~11 K and 17 K, respectively

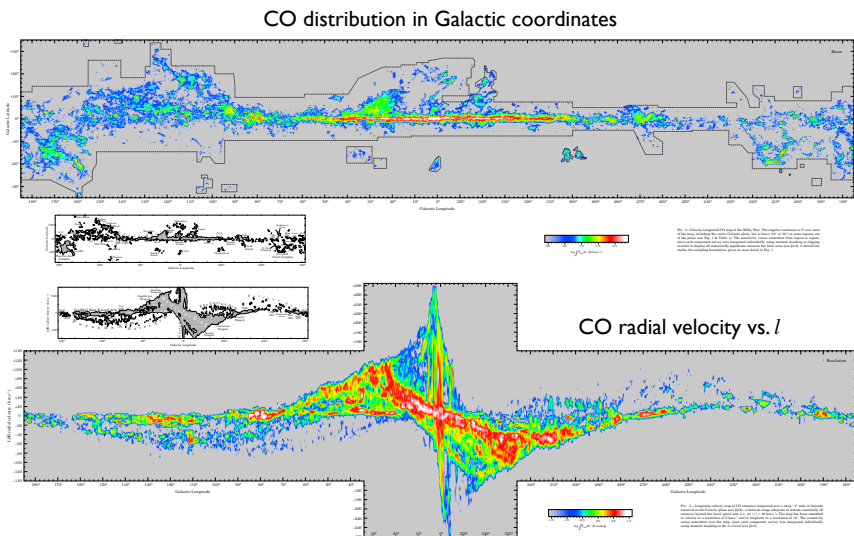
The critical density, at which collisional excitation is in equilibrium with emission, for CO J=1-2 is 700 cm⁻³, typical of giant molecular clouds in the MW

Because H₂ is very difficult to observe directly, we use CO to trace the molecular gas content of the Milky Way (and other galaxies, too!)

We use a conversion between CO intensity and H₂ mass called the “X_{CO}-factor”, which is roughly constant in the Milky Way, but is highly unlikely to be universal, and this uncertainty plagues extragalactic CO observations.

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Molecular gas in the Milky Way



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Molecular gas in the Milky Way

Almost all CO in the MW lies within the Solar circle

Only 20% of HI is at $R < R_0$

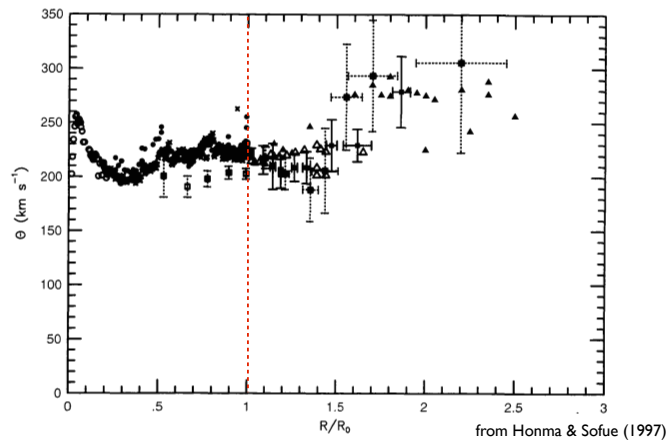
CO concentrated within 4 kpc of GC, with a central hole

By associating CO in the outer Galaxy ($R > R_0$) to young stellar associations, we can use distances to these associations and the velocities of their CO (i.e., their cold molecular gas) to determine the rotation curve of the Milky Way outside of the Solar circle

This is accurate enough to show that the rotation of the Galaxy does not fall as a function of radius beyond the Sun's radius!

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The rotation curve of the Milky Way



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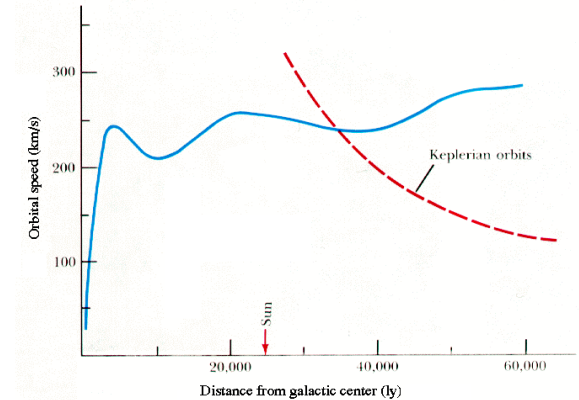
The rotation curve of the Milky Way

If all gas is on circular orbits, and the mass is concentrated at the center of the Galaxy, then Kepler's third law says

$$P^2 = \frac{4\pi^2}{GM} R^3 \text{ and } P = \frac{2\pi}{V} R$$

and so
$$V = \left(\frac{GM}{R} \right)^{1/2}$$

But this isn't what we see!



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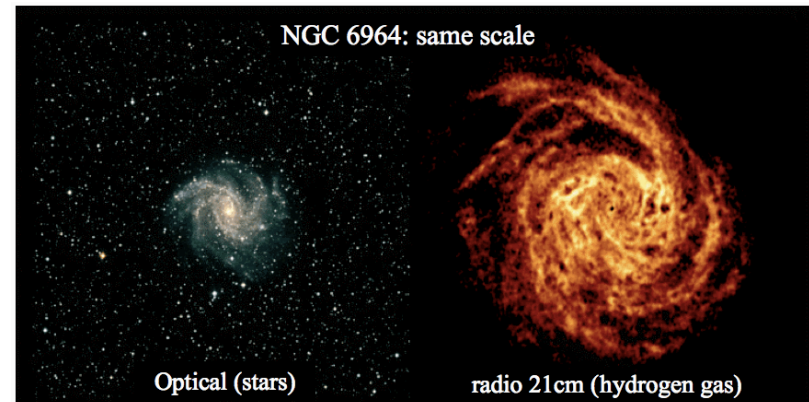
The rotation curve of the Milky Way

We'll see in one of the next lectures that the circular speed V at radius R is related to the enclosed mass $M(<R)$ by

$$M(< R) = \frac{RV^2}{G}$$

If V is close to constant with R , this implies that the mass must grow linearly with radius!

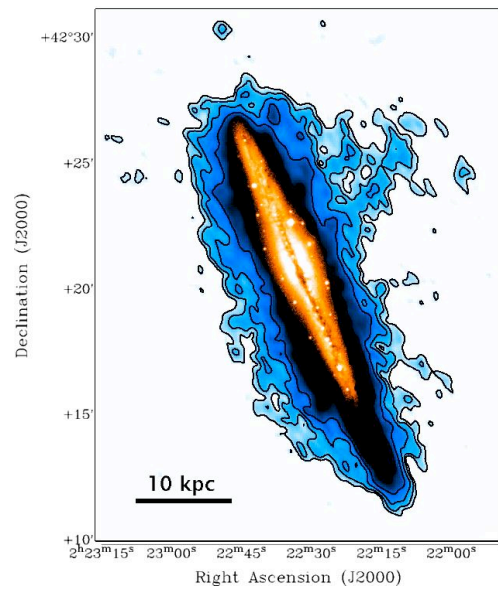
This is why we think that there is dark matter in the Milky Way



Boomsma et al. 2008

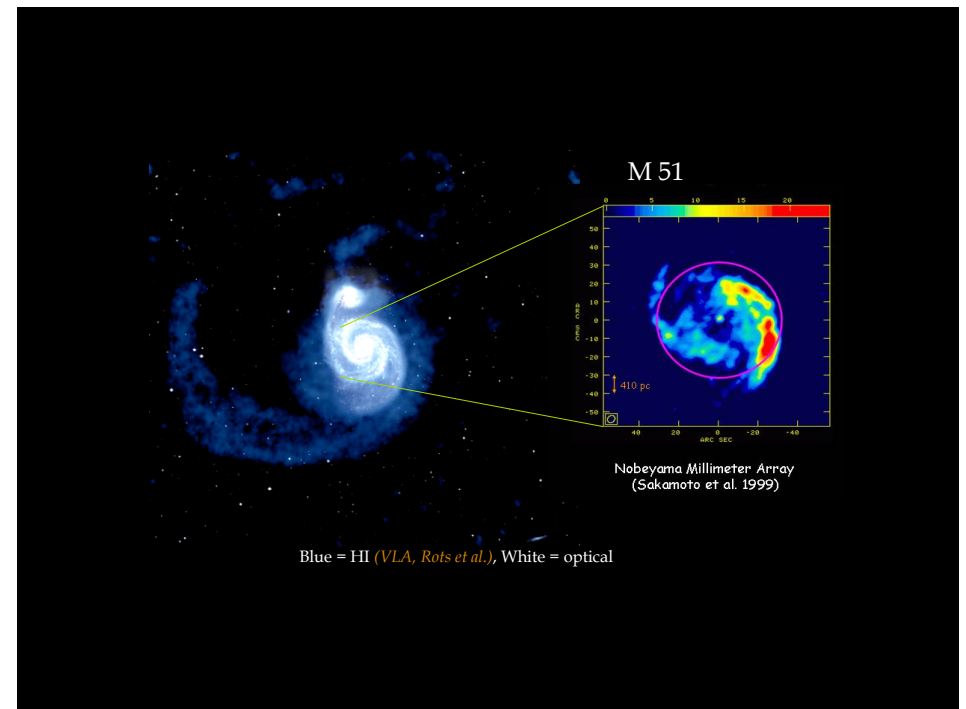
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Oosterloo, Fraternali & Sancisi 2007

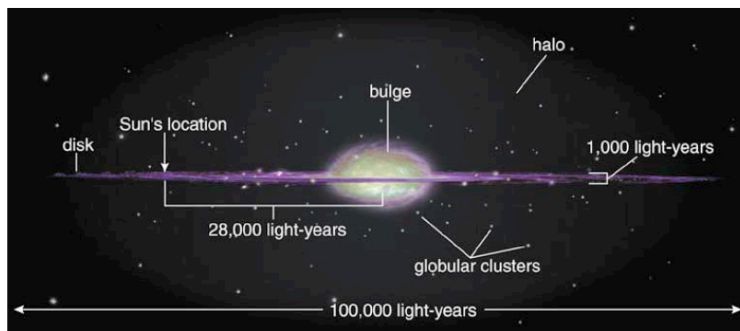
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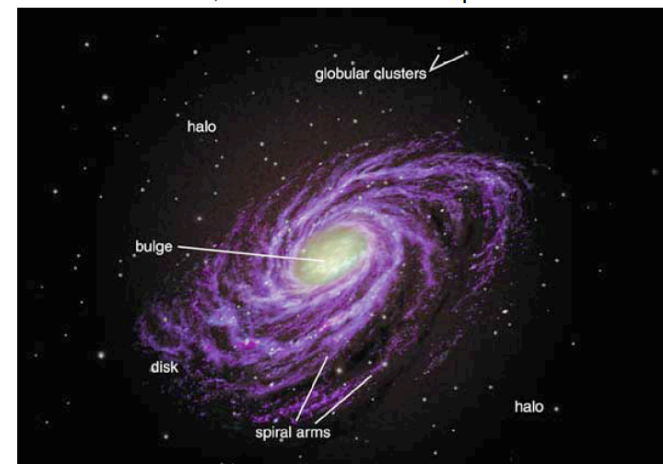
Size of the Milky Way (side view)

- Diameter ~ 100,000 light years
- Thickness ~ 1,000 light years (*flatter than a CD !*)
- Distance from Sun to center ~ 30,000 light years
- About 100 billion stars in total.



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If we could view the Milky Way from above the disk, we would see its spiral arms



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