PHYS2160 – Lecture 5 – The Milky Way (4)

Last time

- Interstellar medium components – HI, H_2 and HII regions.
- Dust and Extinction and Optical Depth
- Stromgren spheres
- Making stars.
- Jeans Criteria for cloud collapse. Plus complications – turbulence, magnetic fields, angular momentum
- Angular Momentum → Accretion disks → Planetary formation
- Exoplanet detection via transits and radial velocity ("Doppler Wobble")
- The planets we find don't necessarily look like the Solar System → Solar System may not be representative. In particular migration of giant planets clearly takes place.

This Time

- Radio wavelength emission mechanisms – Synchrotron, Bremstrahlung, HI 21cm, CO millimetre
- Galaxy rotation curves from the gas
- Dark matter. Searches for dark matter
- Formation models for the Galaxy

PHYS2160 – Lecture 5 – Milky Way (4)

Synchrotron Radiation

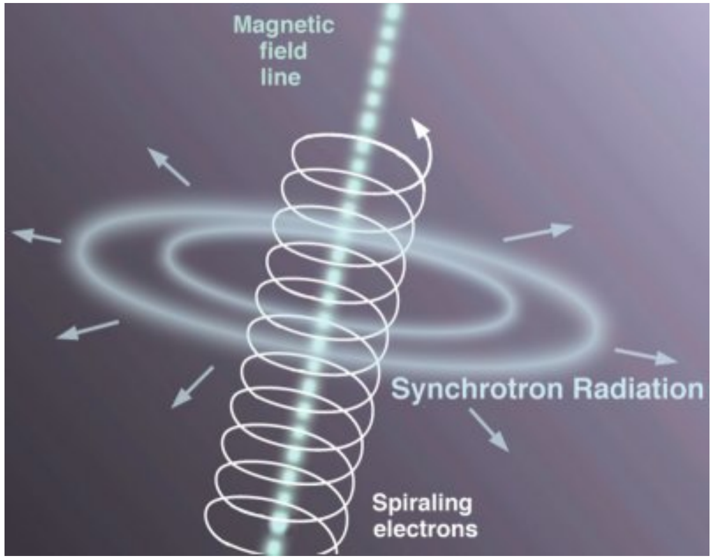
A relativistic electron moving with velocity vector $\mathbf{v}$ in a magnetic field $\mathbf{B}$, is subject to a force

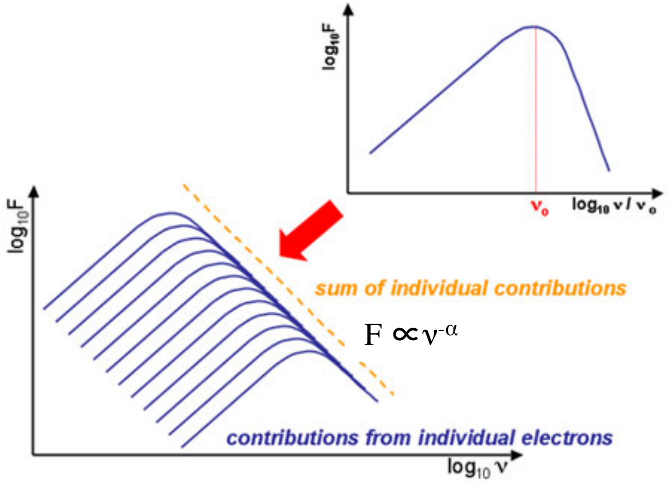
$$-e\mathbf{v}/c \times \mathbf{B}$$

and so will spiral around the magnetic field lines. This acceleration causes the electron to radiate photons along the instantaneous direction of motion.

Such radiation is detected from many classes of astronomical object (though was first encountered in terrestrial particle accelerators) and is often referred to as "non-thermal" emission – the detailed shape of the emission spectrum is a function of the energy distribution of the electrons (rather than a temperature.)

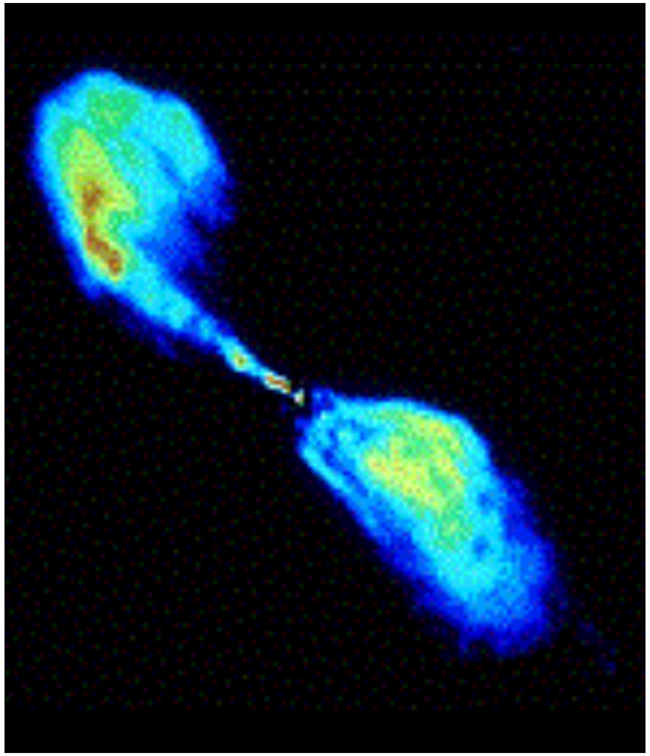
Synchrotron radiation is detected at radio wavelengths and typically has an integrated power law spectrum of form $F \propto \nu^{-\alpha}$, where α is a power law index in the range 0.5-2 (so flux increases as frequency decreases).





PHYS2160 – Lecture 5 – Milky Way (4)

Synchrotron Radiation



Centaurus A (also known as NGC 5128) is a peculiar galaxy in the constellation of Centaurus. The false colour image is a radio one from the VLA showing its synchrotron emission. The image on the left has the optical light from the galaxy superimposed.

PHYS2160 – Lecture 5 – Milky Way (4)

Thermal Bremstrahlung Radiation

Consider an electron in a HII region travelling past an ion. The Coulomb interaction deflects the electron changing its kinetic energy, and this energy loss is emitted as photons.

The electron kinetic energies are generally low, so the resulting photons emitted lie in the infrared or radio. Integrating this process over many electrons with many possible energies, the emission spectrum from an ensemble of particles will form a continuum.

This form of radiation is sometimes called "thermal" emission. The name "bremstrahlung" comes from the German phrase "braking radiation". It is also known as "free-free emission".

The inverse process can also happen (i.e. an electron absorbs a photon in the vicinity of an ion). This process is then known as "free-free absorption".

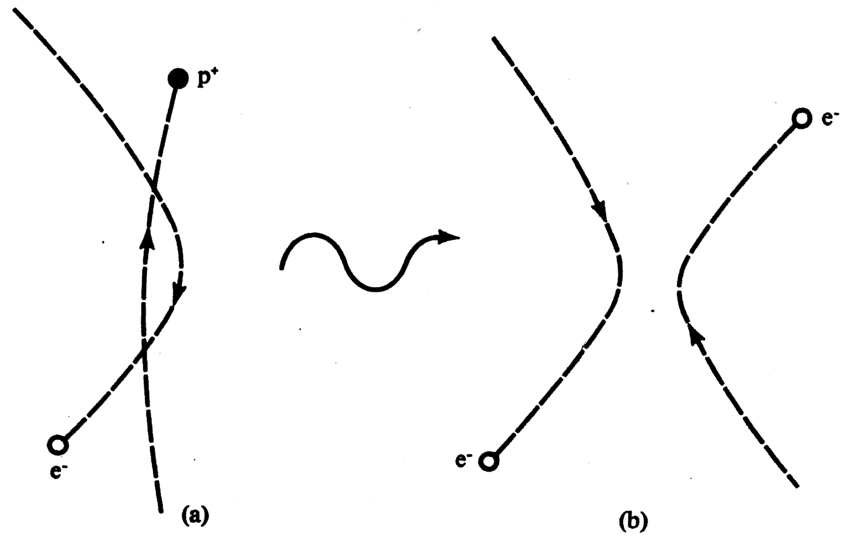


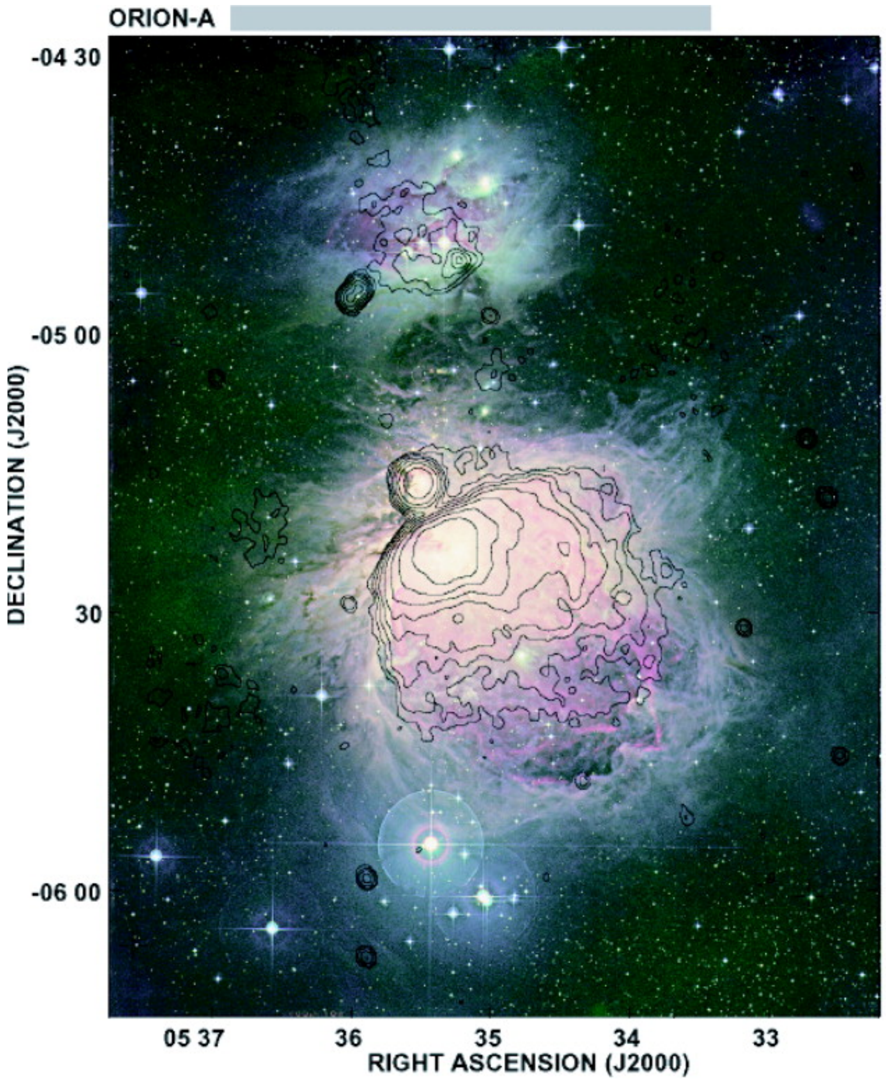
Figure 11.14. The microscopic mechanism responsible for producing thermal radio continuum (free-free emission). (a) A free electron is momentarily deflected by the electric attraction of a passing ion (usually a proton in an HII region). In the acceleration process, the electron radiates a number of photons. The energy carried off by photons of different frequencies (speed of light divided by wavelength) is a pretty flat distribution at radio frequencies, because the encounter time is short compared to the period of vibration of radio waves. (b) When two free electrons deflect one another by their mutual electric repulsion, no net radiation emerges. The oscillatory parts of the electric field associated with accelerating electrons (see Fig. 2.9) exactly cancel when we have two electrons possessing equal but opposite motions.

PHYS2160 – Lecture 5 – Milky Way (4)

Thermal Bremstrahlung Radiation

Overlay of VLA 330 MHz radio contours on a UK Schmidt optical photograph of the Orion region. The radio emission is dominated by thermal bremsstrahlung from hot gas ionized by the central stars of the nebula.

(Subrahmanyan et al., 2001, AJ, 407, 121).

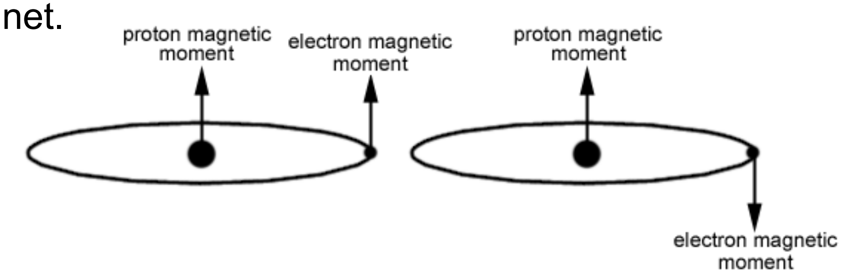


PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – HI : The 21cm Spin Flip Transition

As noted earlier *most* of the ISM is very cold (~10-100K) so H will be in either its atomic (HI) or molecular (H_2) form. Gas in this state is too cold to emit at optical wavelengths. However in 1945 Van de Hulst predicted that atomic hydrogen should be detectable using a 21cm line from HI (and this was discovered experimentally in 1951).

What produces this radiation? Both the proton (*p*) and the electron (e^-) in a hydrogen atom have an intrinsic charge and an intrinsic spin, which combine to generate an intrinsic dipole magnetic field (measured by their *magnetic moment*) – much like a bar magnet.



There are two allowed orientations of these two magnetic moments – either aligned or anti-aligned. When aligned, the *p* and e^- are less tightly bound. And the reverse holds. This means there are two possible quantum states for the hydrogen atom, even when in its electronic ground state – a phenomenon known as *hyperfine splitting*. The transition between these two states in known as a spin-flip transition, and has very low energy (corresponding to a frequency of 1.420406Ghz or ~21cm).

Collisions in the ISM are responsible for changing the hyperfine state of H atoms, at a rate of about one transition every 400 years. Spontaneous emission (never seen in the laboratory) occurs about once per atom every few million years.

As a result, quite long path lengths are require to integrate up enough H atoms to actually see the 21cm line. On the other hand, the line is rarely optically thick, so it probes structures as far as the other side of the galaxy. And building receivers to detect radiation at 1.4Ghz is relatively straightforward, so a lot of our knowledge of the state of the structure of our Galaxy and other galaxies comes from HI observations.

PHYS2160 – Lecture 5 – Milky Way (4)

HI : The 21cm Spin Flip Transition

Kalberla & Kerp, Annu. Rev. Astron. Astrophys. 2009. 47:27–61

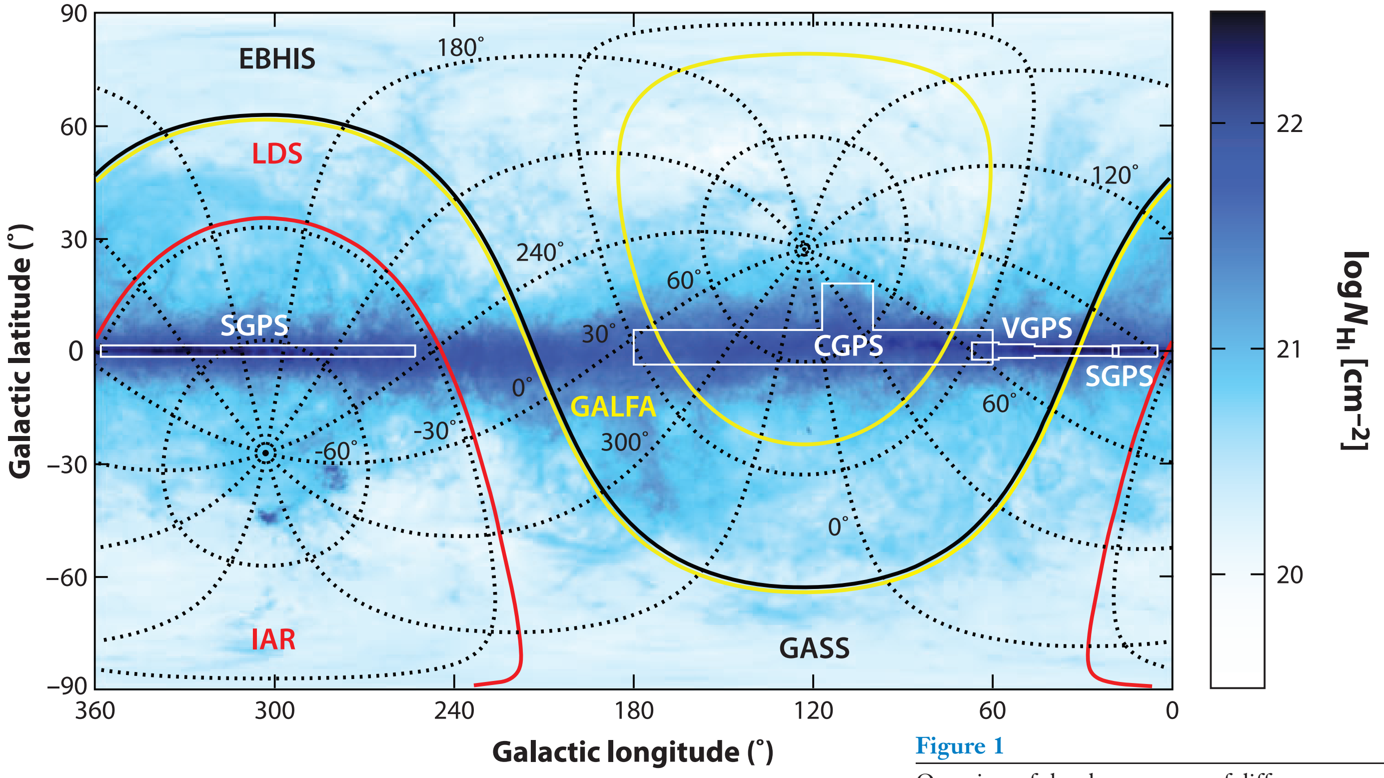


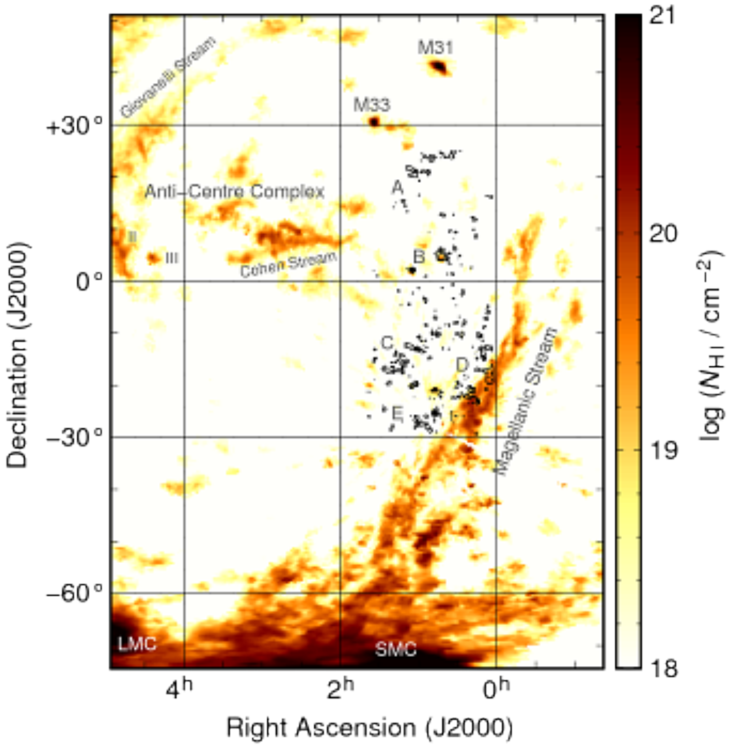
Figure 1

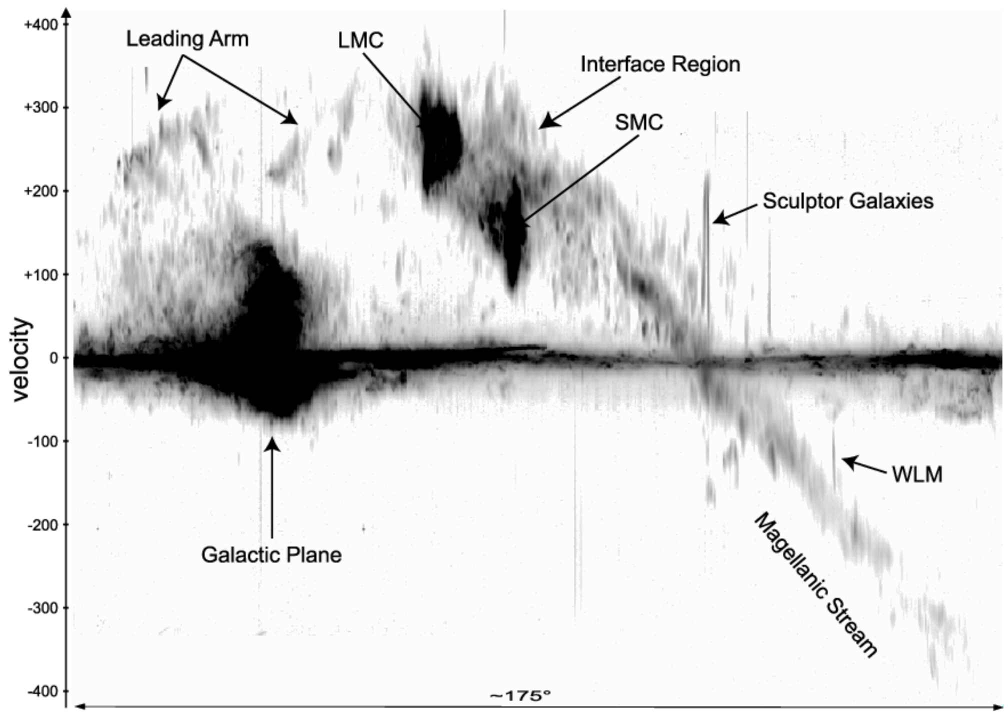
Overview of the sky coverage of different surveys. The Leiden-Argentine-Bonn (LAB) survey merges the Leiden-Dwingeloo Survey and Instituto Argentino de Radioastronomía surveys at $\delta = -27.5° \pm 2.5°$ (*red line*). The Galactic All-Sky Survey and Effelsberg-Bonn HI Survey cover the northern and southern sky, separated by the black line. The Arecibo Galactic ALFA survey coverage is $-2° < \delta < +38°$ (*yellow lines*). The Galactic plane survey consists of Southern Galactic Plane Survey, Canadian Galactic Plane Survey, and VLA Galactic Plane Survey. The background image displays the total volume density of the 21-cm line emission from the LAB survey. This figure was kindly provided by B. Winkel.

PHYS2160 – Lecture 5 – Milky Way (4)

HI : The 21cm Spin Flip Transition

As well as total flux density, we can look at velocity information in the data (e.g. right - Brüns et al. 2005, A&A, 432, 45-67) which shows a survey of a strip of the sky along the line of the Magellanic Stream. Velocity information allows the separation of the Galaxy and Magellanic components.





PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – More on Galactic Kinematics

We saw earlier how we can use data on the radial and tangential velocities of nearby stars to probe the structure of the Galaxy disk using the Oort constants.

We can also use an extension of those techniques to interpret velocity data from *gas* (e.g. HI). In this case we can see *much* further through the Galaxy, though we only detect information on the velocity along the line of sight.

Starting (as before) from

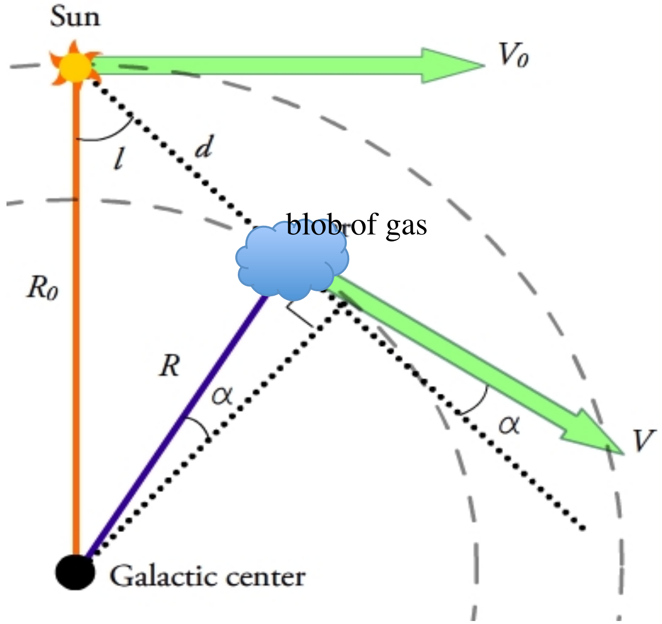
$$V_{\rm obs,\ r} = V_{\rm star,\ r} - V_{\rm sun,\ r} = V\cos(\alpha) - V_0 \sin(l)$$

we get

$$V_{obs} = V - V_0 = V \cos\alpha - V_0 \sin l$$

We can see that the *maximum* value of the velocity we can see along the line of sight will come from the gas lying at α=0 (i.e. at the location where the tangent to the circular velocity is completely along the line of sight. Some trigonometry (see the tutorial problem set) allows one to determine that the maximal radial velocity $v_{r,max}$ obeys

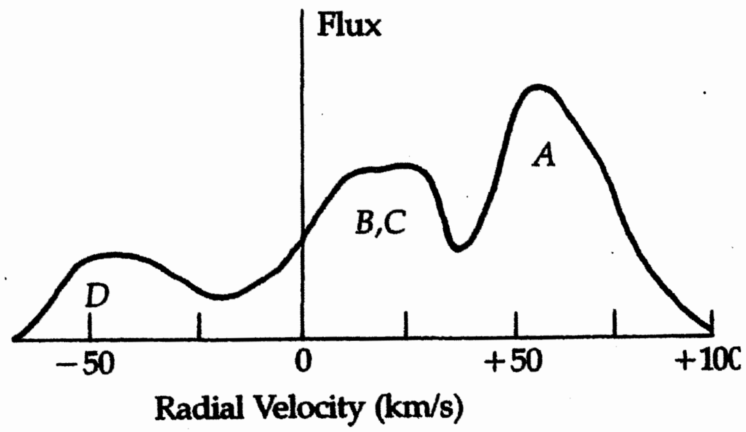
$$v_{r,max} = 2\,A\,R_0\,(\sin l)(1 - \sin l)$$



While the detailed flux emission along a line of sight will depend on the integrated column density along that line of sight (which we don't know), determining the *maximum* velocity is straightforward. By determining the maximum velocity as a function l, we can determine AR_0. And if we know R_0, we then have a *independent* way of determining the Oort constant A.

PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – Measuring the Maximum Velocity



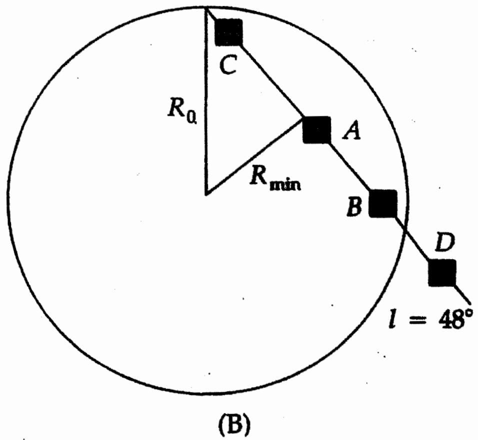


Figure 20–2 Line profiles and Doppler shifts. (A) Line profiles from an umber of H I clouds at longitude 48°. (B) The line-of-sight geometry for the profiles in (A).

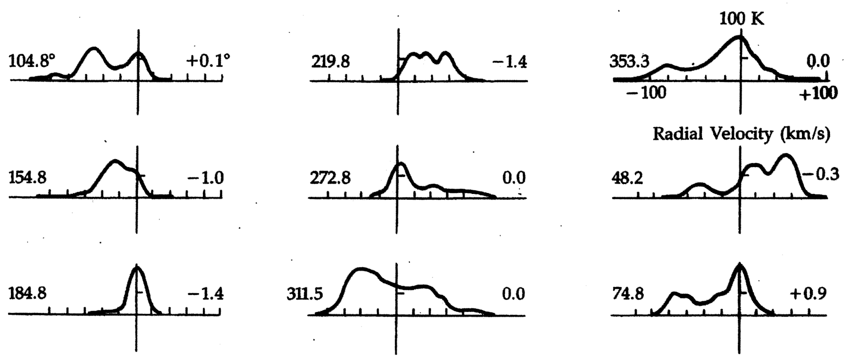
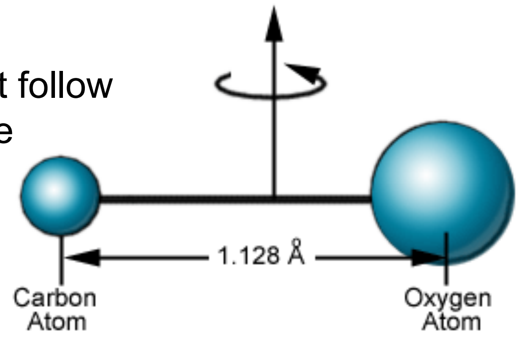


Figure 20–1 Line profiles at 21 cm in the galactic plane. These emissions come from regions spanning the galactic equator. Galactic longitude is indicated on the left of each profile; galactic latitude, on the right. The flux is calibrated in units of the antenna temperature. *(Adapted from diagrams by F.J. Kerr and G. Westerhout)*

PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – H_2: Molecular gas via CO

Consider a diatomic molecule such as CO, or O_2, or H_2. They can spin and they can vibrate. These rotational or vibrational modes are quantized, and must follow a set of quantum mechanical rules. The energies associated with vibration state transitions correspond to infrared wavelengths, while rotational transitions produce lines at radio wavelength.



However, because H_2 contains two identical atoms it has no permanent electric dipole moment, and so has no rotational quantum states. Moreover, its vibrational states cannot be excited by the temperatures present in molecular clouds. So we cannot observe H_2 directly.

Fortunately, CO *is* present in molecular clouds and it does have a dipole moment, with a base rotational transition (J = 1 to 0) resulting in a spectral line at 115.2712 GHz, and a sequence of transitions at longer wavelengths – the J = 2 to 1 transition gives a line at 230.5424 GHz. This 2-1 transition near 3mm was the first to be widely used to probe the molecular clouds of our Galaxy in the 1980s.

These maps show us that star formation happens in the denser molecular clouds (not in HI clouds)

They also show us that it is the molecular gas clouds which trace out the spiral arms in our Galaxy (the arms can also be seen in HI, but are much weaker and more difficult to interpret). *The spiral arms are features of the gas component of the Galaxy.* They are also traced out by young and massive (i.e. recently formed) stars. But they are not seen in older populations of disk stars.

PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – CO tracing H_2 in the Milky Way

e.g. Dame et al. (2001), ApJ, 547, 792 http://www.cfa.harvard.edu/mmw/MilkyWayinMolClouds.html .

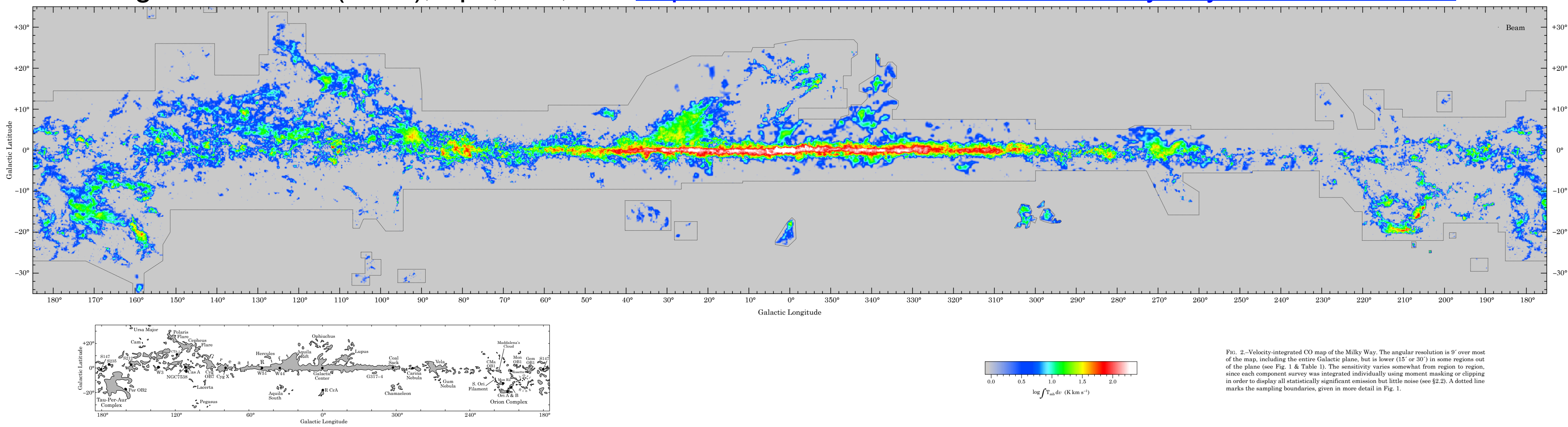


FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

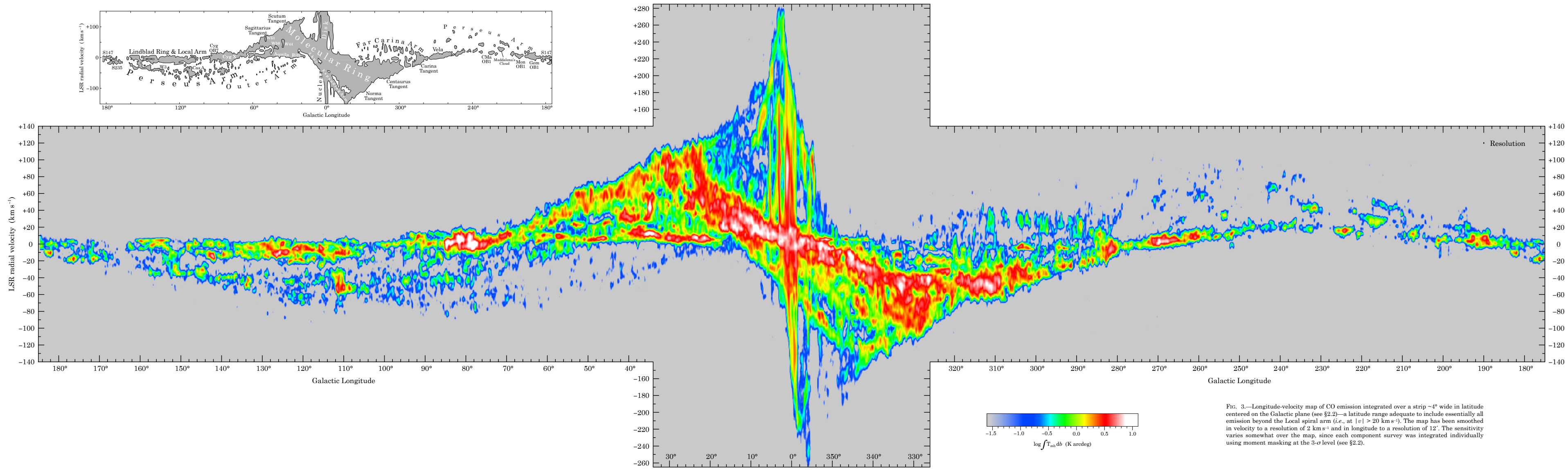
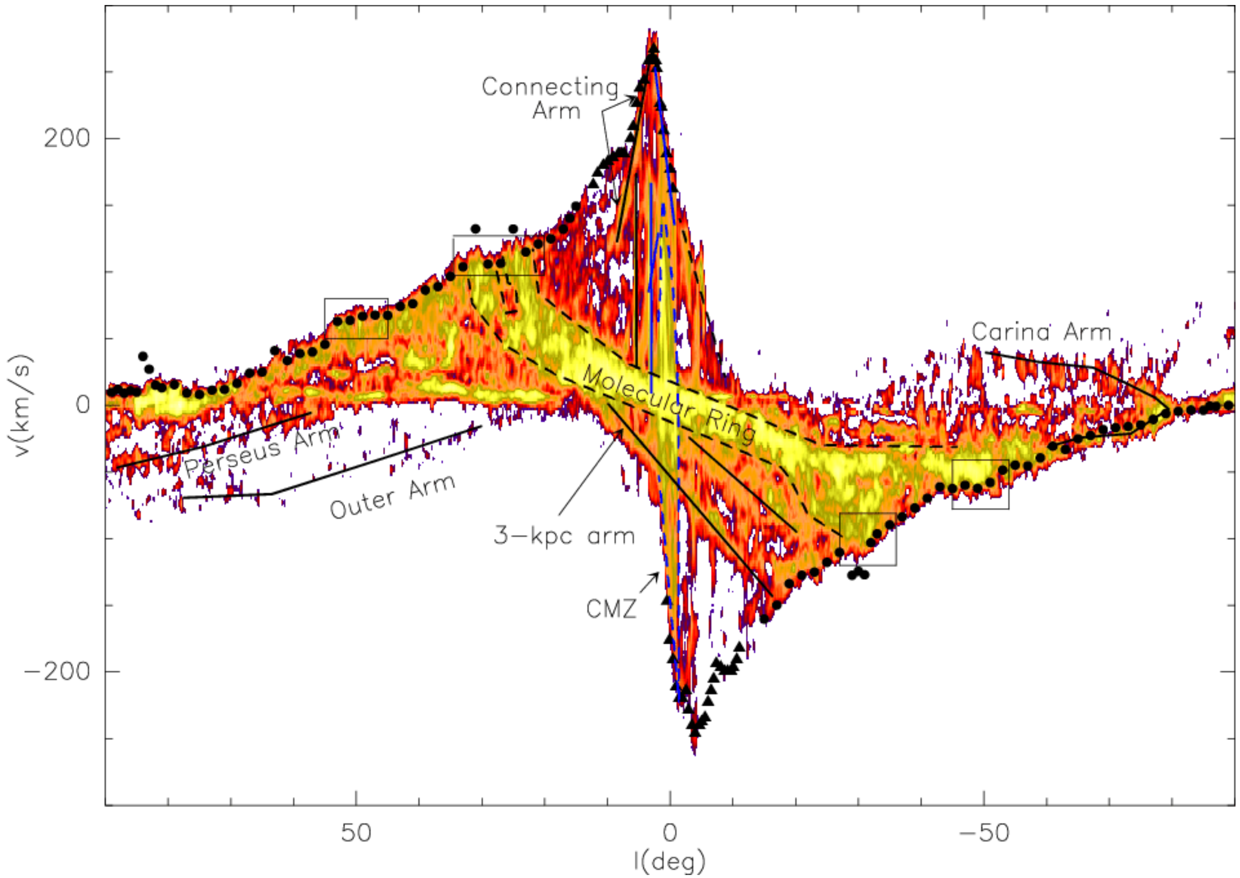


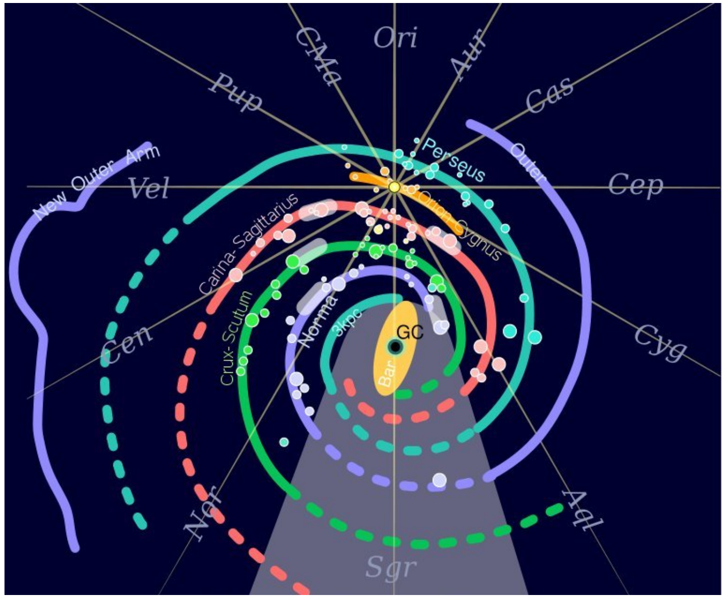
FIG. 3.—Longitude-velocity map of CO emission integrated over a strip ~4° wide in latitude centered on the Galactic plane (see §2.2)—a latitude range adequate to include essentially all emission beyond the Local spiral arm (*i.e.*, at $|v| > 20$ km s^{-1}). The map has been smoothed in velocity to a resolution of 2 km s^{-1} and in longitude to a resolution of 12′. The sensitivity varies somewhat over the map, since each component survey was integrated individually using moment masking at the 3-σ level (see §2.2).

PHYS2160 – Lecture 5 – Milky Way (4)

Seeing Gas – CO tracing H_2 in the Milky Way

Detailed analysis finds correlated structures that can be associated with spiral arms (e.g. Rodriguez-Fernandez & Combes, A&A 489, 115, 2008).

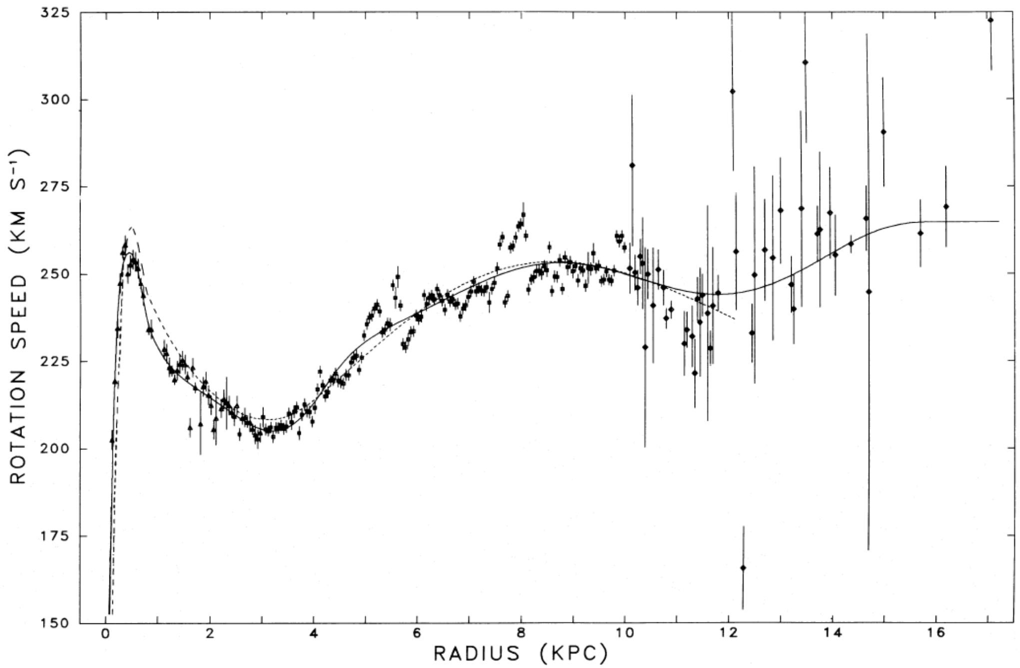




PHYS2160 – Lecture 5 – Milky Way (4)

Rotation Curves – The Dark Matter Halo

Using HI and CO astronomers have been able to trace the Galaxy's rotation curve in towards the Galactic centre, and beyond the radius of the Sun.



It came as a great surprise to astronomers to discover that the rotation curve of the Galaxy is essentially constant beyond R_0 (e.g. figure above from Clemens (1985) ApJ, 295, 422). The fact that the curve does *not* drop off as $\propto R^{-1/2}$ (i.e. Keplerian motion) suggests there is a significant amount of mass beyond R_0.

This is especially surprising as most of the **luminosity** of the Galaxy is produced by matter residing inside the solar radius R_0.

PHYS2160 – Lecture 5 – Milky Way (4)

Rotation Curves – The Dark Matter Halo

What does $V(R)$=constant mean? To see, assume $V(R)=V=constant$. Then from the equation for the centripetal force on a particle at radius r, and from Newton's laws of gravity, we have for a particle with mass m and mass interior to the circular orbit M_r

$$mV^2/r = GM_r m/r^2$$

(We use r for a spherically symmetric mass distribution here, rather than R for a cylindrical rotation in the Galactic plane. However to obtain the rotation curve within the plane we need only set r=R). Solving for M_r and *differentiating* wrt r we get

$$dM_r/dr = V^2/G$$

We can obtain another expression for dMr/dr for a spherical mass distribution $\varrho(r)$ using conservation of mass,

$$dM_r = \varrho\ 4\pi r^2\ dr$$
$$dM_r/dr = \varrho\ 4\pi r^2$$

And equating these

$$\varrho(r) = V^2/(4\pi G r^2)$$

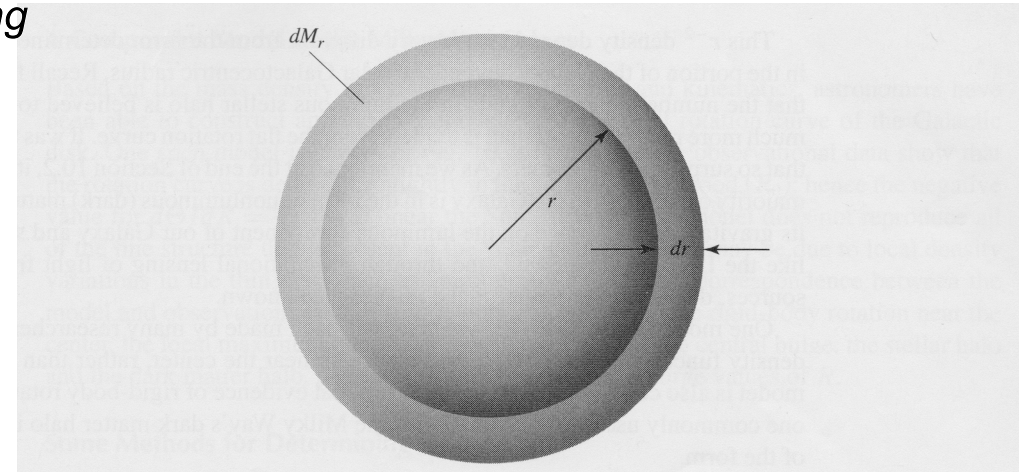


FIGURE 10.25 A spherically symmetric shell of mass dM_r having a thickness dr and located a distance r from the center. The local density of the shell is ρ.

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Rotation Curves – The Dark Matter Halo

This simple argument shows that a flat rotation curve requires a spherical mass density that drops as r^{-2}.

Recall that this is a *much* slower drop off than the $r^{-3.5}$ distribution of both the bulge population at the Galaxy's centre and the stellar halo.

The figure to the right shows a model for the contributions of the known components to the rotation curve (the 'Bulge' here combines the bulge and stellar halo).

There must be some source of non-visible, non-luminous matter making up this halo.

This "**dark matter halo**" is composed of a material that remains unidentified to this day.

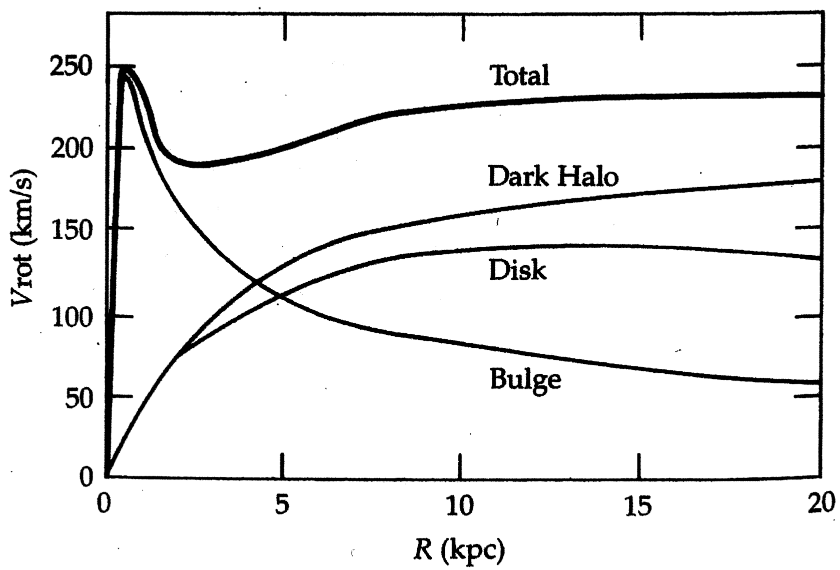

Figure 20–8 A model of the mass distribution of the Galaxy, as represented by rotation curves for each component. The Sun's distance is assumed to be 8.5 kpc. The line marked "Total" should match the observed rotation curve. *(Adapted from a diagram by P.C. van der Kruit)*

PHYS2160 – Lecture 5 – Milky Way (4)

Models for the Formation of the Milky Way

Two models dominate thinking on how the Milky Way formed and evolved – however, this remains an active area of research to this day …

Eggen, Lynden-Bell & Sandage (ELS) Model first proposed in 1962 in which there was a rapid dissipationless collapse of a proto-Galactic nebula. The oldest stars formed early in the collapse on nearly radial trajectories, producing highly elliptical orbits above and below the plane. These earliest stars are metal poor (Population II) as the interstellar medium has not had time to become enriched by the products of stellar nucleosynthesis.

Later, the collapse slowed and became dissipational as energy was converted into random motions in the clouds. The (small) angular momentum in the initial cloud meant that it began to rotate more rapidly as it contracted. The combination of increased dissipation and increased angular speed led to the formation of the disk from which Population I stars began to form (and continue to be formed to this day).

Unfortunately there are some problems – ELS predicts the globular clusters to form early in the rapid collapse (on timescales of 10^8 years). Observations of globular clusters though, show them to have a spread of ages (~2Gyr) and a spread in metallicities. The disk has also been found to have at least two separate components – a *thick* disk and a *thin* disk (we live in the thin disk – the thick disk hosts stars with a scale height several times larger than the thick disk, and quite different elemental abundances).

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Models for the Formation of the Milky Way

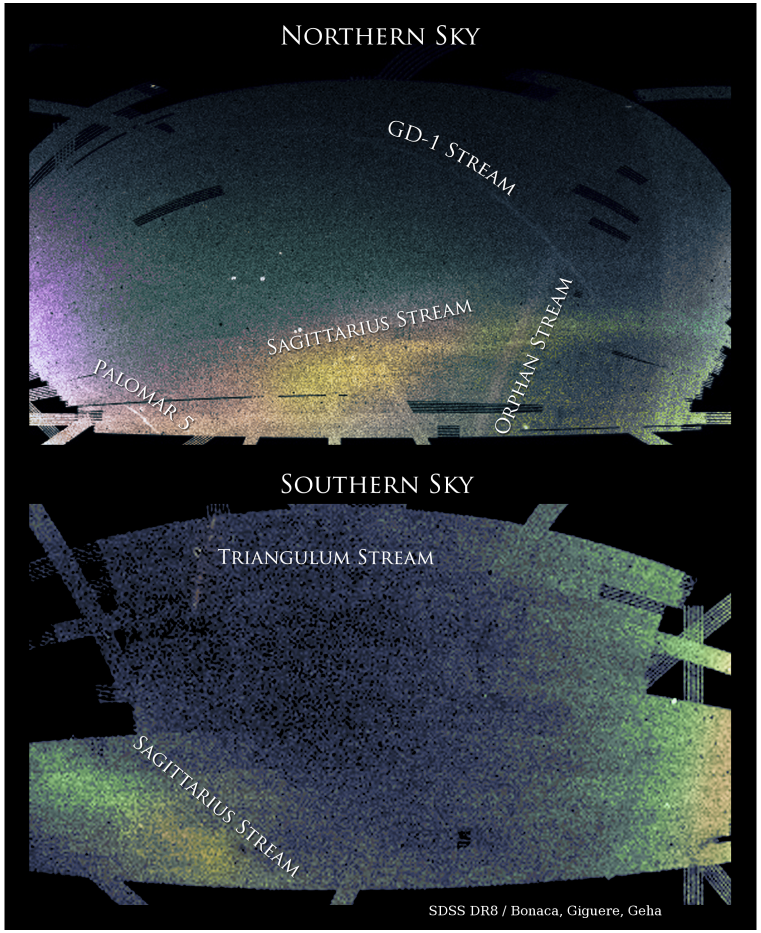
Hierarchical Merger Model (sometimes Searle & Zinn or 'SZ').

Galaxy building appears to have been a 'bottom up' merger process (as well as a 'top down' collapse). Indeed, galaxy formation theories for *other g*alaxies are today dominated by the model that all galaxies form via the accretion of smaller units into larger and larger units.

SZ proposed the Galaxy was built up as a chaotic accretion of individual small (or "dwarf") galaxy units (10^7-$10^9 M_\odot$). Each of these had its own star formation history, leading to a dispersion in the resulting cluster and stellar population properties in the Galaxy. While most accretion takes place in the first 2-3Gyr, some accretion of components takes place to this day.

Indeed, in the last decade or so, several 'streams' have been uncovered in large sky surveys that appear to be the remains of dwarf galaxies that have been disrupted by repeated passages through the Milky Way – especially the Sagittarius stream (image to right from http://www.astro.yale.edu/abonaca/research/halo.html)

In reality both processes are likely to have played a role. Unravelling the Milky Way's complex history remains an active area of research right now (e.g. GALAH survey presented in last slide of Lecture 3 – ask Sarah Martell about this in Part II).



PHYS2160 – Lecture 5 – Milky Way (4)

- References
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- Bibliography
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Useful constants, units, and formulae:

Gravitational constant	G	=	6.67	×	10^{-11}	N m^2 kg^{-2}
Speed of light	c	=	3.00	×	10^{8}	m s^{-1}
Planck constant	h	=	6.626	×	10^{-34}	J s
Boltzmann constant	k	=	1.38	×	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	=	5.67	×	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	=	1.67	×	10^{-27}	kg

Solar mass	$M_\odot$	=	1.99	×	10^{30}	kg
Solar radius	$R_\odot$	=	6.96	×	10^{8}	m
Earth mass	$M_\oplus$	=	5.98	×	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	=	6.378	×	10^{6}	m
Mass of moon	M_{moon}	=	7.3	×	10^{22}	kg
Astronomical unit	AU	=	1.496	×	10^{11}	m
Parsec	pc	=	3.086	×	10^{16}	m
Hubble's constant	H_0	=	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	=	$5 \log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	=	$2.5 \log \frac{f_1}{f_2}$
For small recession velocities	v/c	=	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	=	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	=	$h\nu$
Frequency and wavelength	c	=	$\nu\lambda$