Chapter 3

The modern view of the Milky Way

CO §24.2

3.1 New technologies

3.1.1 Radio astronomy

'Radio-waves' is a generic name for EM radiation with long wavelength λ (somewhat arbitrarily taken to be $\lambda > 1$ m) not susceptible to absorption by interstellar dust. Relevant to galaxies, they can probe the dense, dusty regions where stars form. Earth's atmosphere is nearly transparent for wavelengths 1 cm $< \lambda <$ 10 m. Radio telescopes either consist of a (large) single dish (for example at JODRELL BANK; Ph8 has a small dish on its roof) or an *interferometer* with many inter-connected antennae, for example the *Giant Meter Radio-telescope* (GMRT) in India. Radio-observatories separated by 100-1000s of kilometres sometimes combine their signal to obtain very high angular resolution images[1]. In their wildest dream, astronomers think of building radio-telescopes on the dark side of the Moon (to be shielded from radio signals from Earth) or even in space.

[1] Recall that the angular diffraction limit depends on telescope diameter D and observed wavelength λ as $\theta \propto \lambda/D$. A radio-interferometer with $D = 10^3$ km and $\lambda = 1$ mm has $\theta \approx 10^{-9}$, whereas an optical telescope with $D \sim 10$ m and $\lambda \sim 5\times10^{-5}$ m has $\theta \approx 5\times10^{-8}$.

Just as with optical light, you can think of sources that generate a continuum radio-signal or sources that generate lines (In optical light, the analogy would be a black-body spectrum generating EM-radiation over the whole EM spectrum, as compared to emission or absorption lines created by electronic transitions in atoms or ions - for example the Balmer series in the H I atom). Physical processes that generate radio waves include

1. Roto-vibrational transitions in molecules (lines)
2. Thermal radiation from (cold) dust (continuum)
3. Synchrotron radiation from electrons moving in a magnetic field (continuum)
4. Hyperfine transitions, *e.g.* the 21-cm line in hydrogen (see Ch 4, a line)

Roto-vibrational transitions correspond to the rotational or vibrational transitions in molecules. For example energy can be stored in the vibration of the C and O atoms in a CO molecule, whereby the distance between C and O varies. A quantum transition whereby the amount of vibration in the molecule decreases is associated with the emission of a photon. A diatomic molecule such as CO can also store energy in rotation along one of the two axes perpendicular to the C-O molecular bond. A decrease in the amount of rotation again results in the emission of a photon. The associated energies ΔE are in general much less than of *electronic transitions* hence the associated wavelengths $\lambda = hc/\Delta E$ are longer (IR or radio-waves, as opposed to optical or UV-radiation).

Thermal radiation Dust heated by nearby stars cools by radiating radio/infrared waves. If the dust temperature is low, the black-body may peak in micro/mm wavelengths[2]

Synchrotron radiation Electrons moving in a magnetic field may emit radiation at radio-wavelengths depending on their speed (just as in a terrestrial synchrotron). Astronomical examples include supernovae remnants, and AGN discussed in a later chapter.

[2]Recall Wien's displacement law, relating the peak emission wavelength λ and temperature T as $\lambda = b/T$, with $b = 3 \times 10^{-3}$ m K. .

The 21-cm line is discussed in more detail in the next chapter.

Recent new radio-telescopes include LOFAR in the Netherlands, which has stations throughout Europe, the Atacama Large Millimeter Array in Chile (ALMA), and path-finders to the Square Kilometre Array (SKA) such as MEERKAT in South Africa and WALLABY in Australia, as well as the giant FAST telescope in China.

3.1.2 Infrared astronomy

IR photons are not significantly absorbed by dust either. In fact, much of the visible and UV-light absorbed by dust grains, is re-emitted in the IR and sub mm, and so IR observations can look deep inside star forming regions. The DIRBE instrument on the COBE (Cosmic Background Explorer) satellite provided us with one of the best views of the the Milky Way, because it could see through the dust clouds that obscure large parts of the MW in the optical. Unfortunately earth's atmosphere absorbs most IR radiation, except in some narrow bands. IR observations therefore require balloon, rocket or satellites, or are limited to narrow regions of EM radiation in between the atmosphere's absorption bands.

3.1.3 Star counts

The HIPPARCOS satellite used diffraction limited observations above the atmosphere to obtain superbly accurate positions of stars on the night sky. By repeating measurements over several years, the satellite measured parallaxes of many 1000s of stars, and in addition proper motions for some stars (*i.e.* the velocity of some stars in the plane of the sky). Parallax distances are the crucial first step to the distance-ladder: parallax distances to Cepheids are required to calibrate the period-luminsity relation.

GAIA, the successor to HIPPARCOS, was launched in November 2013 and is currently taking data. Once its mission is completed, it will have measured positions on the sky of billions of stars to astonishing precision. Its measurements are so accurate that it can determine the motion of stars in the plane of the sky, simply by measuring positions as a function of time. It will revolutionize our understanding of the MW. You may want to spend some time exploring the brilliant website of this mission - use the link above.

Fig. 3.1 shows the striking difference in how the MW appears when observed in different wave lengths. This is partly because the source of the EM radiation is different (e.g. super nova remnants in the X-rays, versus dust in the IR) and partly because some wave lengths are more absorbed than others.

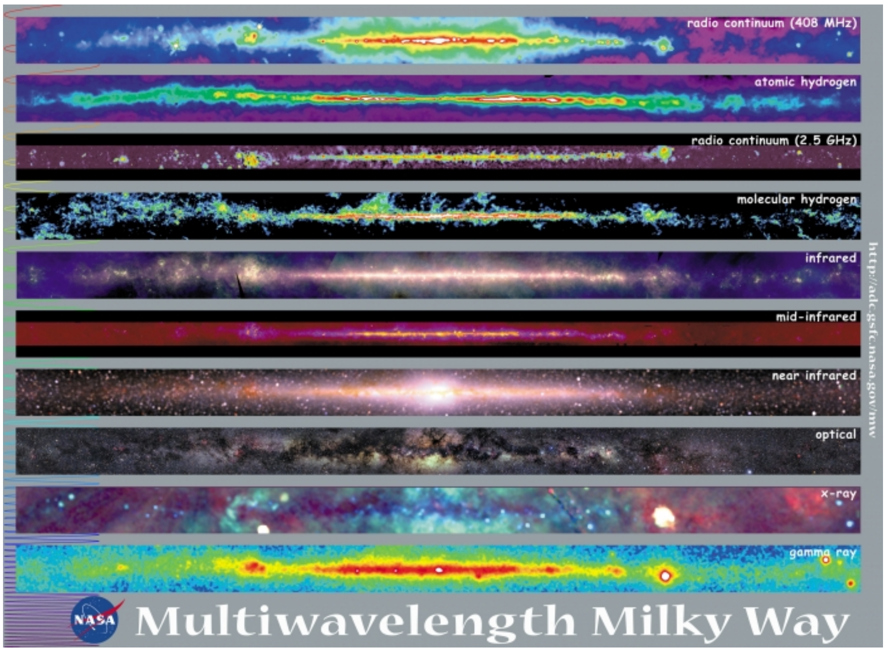

Figure 3.1: NASA's multi-wavelength view of the MW galaxy.

3.2 The components of the Milky Way

The techniques above have shaped our view of the MW: it consist of three well-defined separate stellar systems: *disc*, *bulge* and (stellar) *halo*. A summary of the properties of these is in Tables 3.1 and 3.2.

3.2.1 disc

The disc is a round, thin distribution of stars. The Sun is part of the MWs disc.

- luminosity $L \sim 2 \times 10^{10} L_{\odot}$ in the B-band, ≈ 70 per cent of the MWs total B-band luminosity.

- radius[3] $R \sim 15$kpc.
- Define the thickness t of the disc as the ratio $t \equiv \rho/\sigma$ of the volume density of stars, ρ, in the galactic plane, and the surface density σ. The thickness t depends on the type of star, and is ~ 200pc for young stars, ~ 700pc for stars like the Sun.

The disc also contains gas and dust (see lecture 4 on the interstellar medium). On top of the smooth disc are spiral arms, traced by young stars, molecular clouds, and ionised gas. The disc stars are in (nearly) circular motion around the centre, with speeds $\sim 220\text{km s}^{-1}$. The oldest disc White Dwarfs are $\sim 10 - 12 \times 10^9$ years old, but these could have formed *before* the disc.

The density distribution of stars in disc in cylindrical coordinates (R, ϕ, z) can be written as

$$n(R, \phi, z) \propto \exp\left(\frac{-R}{R_h}\right) \exp\left(\frac{-|z|}{z_h}\right), \tag{3.1}$$

i.e. independent of ϕ since it is cylindrically symmetric, and falling exponentially both in radius R and height z above the disc, with *scale-length* $R_h \approx 3.5$ kpc and *scale-height* $z_h \approx 0.3$ kpc.

Note that there isn't really an edge to the disc, either in radius or height. It can be traced to a distance of around 30kpc. With a height of 0.3kpc, this is a ratio 100:1, which is thinner than a compact disc!

The thick disc About 4 per cent of the MW's stars belong to a thicker disc, aligned with the (thin) disc, but with a larger scale height of $z_h \approx 1$kpc. Stars in this thick disc differ from the thin disc stars discussed above both in composition (having a lower metal content) and kinematically.

3.2.2 Bulge

The bulge is a spheroidal distribution of stars in the centre of the MW (and of most spirals).

- central spheroidal stellar system with radius of ~ 1kpc

[3]The distance from Sun to the galactic centre has recently been determined with remarkable accuracy to be $R_0 = 7.94 \pm 0.42$ kpc, from the observed motions of stars around the galactic centre (see lecture 11 for more details).

- luminosity ≈ 30 per cent of total MW luminosity
- luminosity profile is a de Vaucouleurs or '$r^{1/4}$' profile, defined as

$$I(r) = I_e \exp[-7.67(r/r_e)^{1/4} - 1]\,, \tag{3.2}$$

with *effective radius* $r_e \approx 0.7$kpc.

The bulge stars are generally older and their elemental composition differs from that of disc stars, suggesting that the bulge formed before the disc. Currently, there is little or no star formation in the bulge.

The MW's bulge is not exactly spherical, rather it is ellipsoidal in shape with axis ratio 5:3, and with strong evidence for a bar. Whereas the disc stars are rotating in ordered fashion around the MW centre, the bulge has little net rotation, but the stars have large random velocities. All these properties: no star formation, large random stellar motions, spheroidal geometry, are reminiscent of the properties of an elliptical galaxy: it is as if there is a small elliptical galaxy at the centre of each disc galaxy.

Although the bulge is bright, you cannot see it on the night sky, because its visible star light is absorbed by intervening dust. We need IR observations to make it visible.

3.2.3 Stellar halo

A very small fraction (≤ 1 per cent) of the MWs stars are contained in a large, spheroidal, extremely tenuous stellar system called the (stellar) halo, mostly (99%) made-up out of single 'field' stars with a sprinkling of Globular Clusters. The halo does not appear to rotate, and the halo stars have very low metallicities, typically 1/10 to 1/100 times the solar metallicity. When a halo star occasionally plunges through the disc, it is spotted because of its very high velocity, which is partly due to its intrinsic high random velocity, partly due to the fact the the Sun (and other disc stars) races with 220 km s^{-1} around the MW centre, but the halo star does not partake in this rotation. It is thought that the majority of halo stars is debris from the destruction of MW satellites. When such a small satellite galaxy ventures close to the disc, it is destroyed by the galactic tides, and its stars scattered throughout the halo. Evidence for such destruction is seen in the form of 'tidal streams' streams of stars torn out of a tidally disrupting galaxy. See for example this GAIA web-site.

The halo also contains ≈ 150 Globular Clusters (GCs).

The density of halo stars, and of GCs, falls off with distance r from the centre, as

$$n(r) = n_0(\frac{r}{r_0})^{-3.5}\,, \tag{3.3}$$

and extremely distant field stars have been detected out to more than $\approx$ 50 kpc.

3.2.4 The dark matter halo

See lecture 5 for evidence that as much as 90 per cent of the mass in the MW is invisible, and consists of some unknown type of matter.

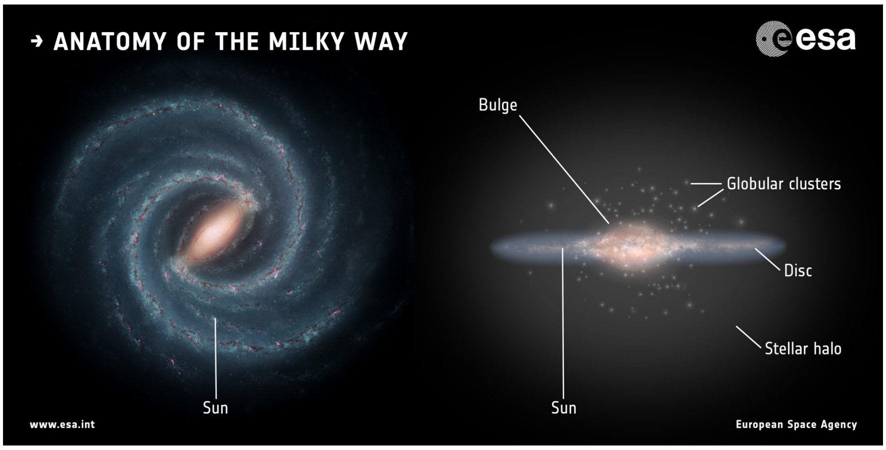

Figure 3.2: ESA's cartoon of the MW galaxy.

3.3 Metallicities of stars and galaxies (CO p.885)

Nucleo-synthesis during the first three minutes after the Big Bang produced mostly Hydrogen and Helium as well as trace amounts of other light elements such as Li and B[4]. By mass, a fraction $X \approx 0.76$ was Hydrogen, with most

[4]See L3 and L4 lectures.

of the remaining mass fraction $Y \approx 1 - X \sim 0.24$ in Helium. All other elements were synthesised in stars and flung into space either due to winds (in AGB stars), during a Planetary Nebula phase, or during supernova explosions[5]. These elements are usually (but inaccurately) referred to as 'metals' in astronomy, and their mass fraction denoted as $Z \equiv 1 - X - Y$.

A star formed out of gas already enriched in metals by (a) previous generation(s) of stars, will have a higher metal fraction Z than stars formed from more pristine gas. Since most of the stellar burning converts Hydrogen into Helium, such a star will have also tend to have $X < 0.76$ and hence $Y > 0.24$. For example the Sun has $X \sim 0.7$, $Y \sim 0.28$ leaving a total fraction of $Z = 1 - X - Y \approx 0.02$ in 'metals'. The composition of a star therefore contains a wealth of information on the properties of earlier generations of stars. It is quite an awesome realisation that the metals in the Sun (and also in you and me) were produced by 1000s of stars and SNe that have long since perished.

Metallicity is often expressed relative to that of the Sun on a logarithmic scale, denoted (for example for Fe) as

$$[\mathrm{Fe/H}] \equiv \log_{10}\left[\frac{M_{\mathrm{Fe}}/M_{\mathrm{H}}}{(M_{\mathrm{Fe}}/M_{\mathrm{H}})_\odot}\right], \tag{3.4}$$

that is (the logarithm of) the ratio of Fe-to-H by mass in the object, divided by that ratio for the Sun. A star with [Fe/H]=0 has the same Fe abundance as the Sun, a star with [Fe/H]=-1 is ten times more Fe poor, a star with [Fe/H]=1 ten times more Fe rich.

MW disc stars have $-0.5 \leq$ [Fe/H] $\leq +0.3$, with a clear trend of increasing [Fe/H] toward the centre of the disc, hence the MWs material has been processed more vigorously in its interior than towards its outskirts. A population of relatively metal rich stars, in a galaxy still undergoing star formation, are called *population I* stars. The true nature of the thick disc stars is not completely clear, but thick disc stars tend to be more metal poor, [Fe/H]≈ -0.6

Bulge stars have a wide range of $-3 \leq$ [Fe/H] ≤ 0.3, with no significant ongoing star formation. This population of relatively metal rich stars in a

[5]Elements heavier than ^{56}Fe are endothermic, meaning energy is required to synthesise them, as opposed to elements that release energy during synthesis, and are almost exclusively produced during SNe explosions.

region not undergoing star formation is called *population II*[6].

Halo stars have much lower abundances $-3 <$ [Fe/H]< -1. A population with such extremely low abundance, composed of old stars, is called *extreme population II*.

Figure 3.3 illustrates the abundance pattern of the Sun.

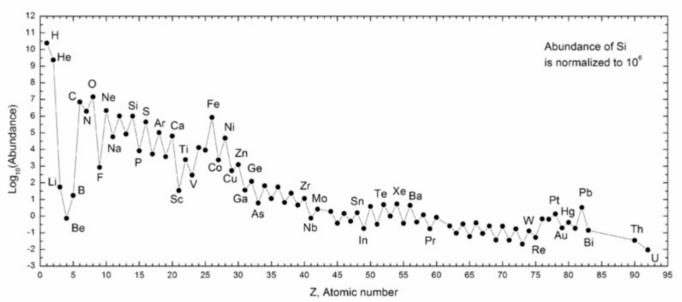

Figure 3.3: Elemental abundances in the Sun reflect the different nucleo-synthetic processes that enriched the gas cloud from which the Sun formed. What is plotted is the relative abundance of various elements, characterized by their atomic number, with respect to Hydrogen. Notice the dominance of H and He - mostly formed during Big Bang nucleo-synthesis, the relatively high fraction of α elements (such as C, O, Ne, Mg etc) whose nucleus is multiple of an α particle (i.e. a He nucleus) synthesized in massive stars, and the general sharp drop in abundance past Fe. Iron is the most bound of all nuclei and fusion of more massive elements does not release energy and hence cannot power stars.

3.3.1 Galactic Coordinates (CO §24.3)

The position of an object on the sky as seen from the Sun can be characterised by two angles (see Fig. 3.4) : (1) *galactic latitude*: the angle b above the Milky

[6] The stellar population of elliptical galaxies is similar

Table 3.1: disc parameters

	Neutral Gas	Thin disc	Thick disc
$M/10^{10}M_\odot$	0.5	6	0.2 to 0.4
$L_B/10^{10}L_\odot$		1.8	0.02
$M/L_{\rm B}$ $(M_\odot/L_\odot)$		3	
Diameter (kpc)	50	50	50
Distribution	$\exp(-z/0.16\mathrm{kpc})$	$\exp(-z/0.325\mathrm{kpc})$	$\exp(-z/1.4\mathrm{kpc})$
[Fe/H]	> 0.1	-0.5 – 0.3	-1.6 – -0.4
Age (Gyr)	0 – 17	< 12	14 – 17

Table 3.2: Spheroid parameters

	Central Bulge	Stellar Halo	Dark Matter Halo
$M/10^{10}M_\odot$	1	0.1	55
$L_B/10^{10}L_\odot$	0.3	0.1	0
$M/L_{\rm B}$ $(M_\odot/L_\odot)$	3	~ 1	-
Diameter (kpc)	2	100	> 200
Distribution	bar	$r^{-3.5}$	$(a^2 + r^2)^{-1}$
[Fe/H]	-3 – 0.3	-4.5 – -0.5	
Age (Gyr)	10 – 17	14 – 17	17

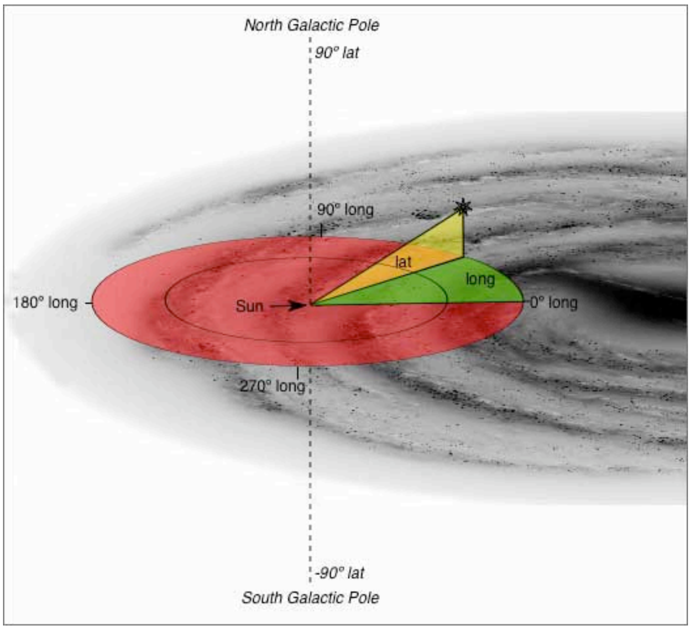

Figure 3.4: Diagram illustrating galactic longitude l and galactic latitude b. From *thinkastronomy.com*.

Way plane and (2) *galactic longitude*: the angle l between the direction Sun-Galactic centre, and the projection Sun-star onto the Milky Way disc.

3.4 Summary

After having studied this lecture, you should be able to

- Explain which processes generate observable radio and IR radiation, and why this radiation was important to clarify the MW structure.
- Explain how the Hipparcos satellite was a major step in setting the scale of the MW, by performing accurate parallax and proper motions measurements, and fixing a reference frame with respect to distant objects.
- Describe the three main stellar components of the MW, and give two characteristic properties of each
- Explain what is meant by the metallicity of a star, and how it is expressed
- Explain how the Galactic Coordinate system (l, b) is defined