# Lecture notes 15: The Milky Way I: Morphology

## A brief history

The word **galaxy** is derived from the greek word for milk, and hence our Galaxy is named the Milky Way system. The band of light associated with the Milky Way is comprised of stars and is acutally our view of the galactic disk from a vantage point more or less in the midplane of the disk.

The true structure of the Milky Way was not been known until recently: William Herschel was the first to attempt to discern the dimensions of the Galaxy and the Sun's place in it by the method of star counting. Later, in the latter nineteenth century, Kapteyn did the same in a much more systematic manner. Both concluded that the number of stars fell of rapidly with distance from the Sun and that the evidence pointed to a model where the Sun was placed more or less centrally in an oblong universe with a ration between the axes of roughly 1/5. However, both were misled by the prescence of great quantities of dust in the galactic midplane where the Sun resides.

**Star counts** Even so, the technique of star counting is an important one, which has many uses as soon as one learns how to compensate for dust absorbtion. Let us quote some useful definitions: $n_L(L, S, \Omega, r)$ – the number density of stars with attribute $S$, in solid angle $\Omega$, at distance $r$, that have luminosities between $L$ and $L + dL$.

$$N_L(L, S, \Omega, d) = \left[ \int_0^d n_L(L, S, \Omega, r) \Omega r^2 dr \right] \tag{1}$$

is the total number of stars in the cone that strectches from the Sun to distance $d$, remembering that the volume element is $dV = \Omega r^2 dr$. What is observed is the total number of stars with fluxes $f$ greater than a certain value, rather than the number of stars at distances smaller than a certain value. This function is written $\bar{N}_L(L, S, \Omega, f)$.

An important special case is the total number of stars at all angles with fluxes greater than some limit — $f > f_0$ — when the density of stars with attribute $S$ is constant. It is given by

$$\bar{N}_L(L, S, f > f_0) = \frac{n(L) L^{3/2}}{3(4\pi)^{1/2}} f_0^{-1/2}, \tag{2}$$

which is left as a proof for the reader.

**Cepheids and the size of the Galaxy** It was Harlow Shapley who discovered the true dimensions of the Milky Way in the early 1920's. Henrietta Leavitt had previously discovered that **Cepheids** — the first of which, $\delta$ Cephei, was discovered to be variable by John Goodricke in 1784 — follow a **period–luminosity relationship** by studying examples of these stars in the Magellenic clouds which are all at roughly the same distance from us. The calibration of such a relationship allows one to find the distance to the star; the observed flux $f$ is related to the luminosity $L$ and distance $r$ via $L = 4\pi r^2 f$.

Cepheids are very luminous yellow supergiants of spectral class F6 or so with periods found between $P = 1 - 50$ dy, but usually 6 to 7 days. The amplitude of the variations is roughly a factor 2.5 and the stars are visible to several Mpc. There are approximately 700 cepheids in the Galaxy. The cepheids are population I, related variable stars that also follow a period–luminosity relationship are the **W Virginis** type variables, which are population II as are the **RR Lyra** stars commonly found in globular clusters and also known as cluster variables. It was the latter type that Harlow Shapley calibrated the period-luminosity relationship for. Studying examples of these stars in several globular clusters (there are more than 200 in the Galaxy), Shapley concluded that they orbit a point some 8000 pc from the Sun, a point Shapley identified as the center of the Galaxy (actually Shapley found a distance of 15 000 pc, having incorrectly calibrated for dust.

### Galactic Morphology

The Milky Way is comprised of several elements as summarized in table .

| | **Disks** | | |
|---|---|---|---|
| | Neutral Gas | Thin Disk | Thick Disk |
| $M(10^{10}M_S)^a$ | $0.5^b$ | 6 | 0.2 to 0.4 |
| $L_B(10^{10}L_S)^c$ | — | 1.8 | 0.02 |
| ) $M/L_B(M_S/L_S)$ | — | 3 | — |
| Diameter (kpc) | 50 | 50 | 50 |
| Form | $e^{-h_z/z}$ | $e^{-h_z/z}$ | $e^{-h_z/z}$ |
| Scale height (kpc) | 0.16 | $0.325^d$ | 1.4 |
| $\sigma_w$ (km s$^{-1}$ | 5 | 20 | 60 |
| [Fe/$H$] | $> +0.1$ | -0.5 to +0.3 | -1.6 to -0.4 |
| | **Spheroids** | | |
| | Central Bulge | Stellar Halo | Dark Matter Halo |
| $M(10^{10}M_S)^a$ | 1 | 0.1 | $55^a$ |
| $L_B(10^{10}L_S)^c$ | 0.3 | 0.1 | 0 |
| ) $M/L_B(M_S/L_S)$ | 3 | $\sim 1$ | — |
| Diameter (kpc) | 2 | 100 | $> 200^a$ |
| Form | bar? | $r^{-3.5}$ | $(a^2 + r^2)^{-1}$ |
| Scale height (kpc) | 0.4 | 3 | 2.8 |
| $\sigma_w$ (km s$^{-1}$ | 120 | 90 | — |
| [Fe/$H$] | -1 to +1 | -4.5 to -0.5 | — |

[a] The total mass may reach $1.3 \times 10^{12}$ $M_S$ within $r = 230$ kpc.

[b] $M_{\rm dust}/M_{\rm gas} \simeq 0.007$.

[c] The total luminosity of the Galaxy is $L_{B,\rm tot} 2.3 \pm 0.6 \times 10^{10}$ $L_S$.

[d] The scale height of the young thin disk is 50 pc.

**Disks** The site of current star formation is the young thin disk. The age of stars is often classified according to the amount of metals (*i.e.* materials heavier than He) in their atmospheres. Population I stars are the youngest with metal fractions on the order $Z \approx 0.02$, population II stars are much older with $Z \approx 0.001$. Of course, stars with metal contents in between these exist and it is perhaps more precise to use the iron content $[Fe/H]$ as an age indicator. This ratio is defined so that

$$\left[\frac{\mathrm{F}e}{H}\right] \equiv \log_{10}(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}) - \log_{10}(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}})_S \tag{3}$$

The ratio is -4.5 for the oldest stars, 0 for the Sun, and +1 for the youngest stars. The derivation of the age-metallicity relation is not as easy as one may think; the proportion of Fe in the Galaxy stems mainly from supernova of type SN Ia which need rougly $10^9$ yr to start exploding. Thus, the ratio of Fe in stellar atmospheres may be misleading for the oldest stars. Perhaps using the ratio $[\mathrm{O}/H]$ is better? Oxygen is produced in supernova of type SN II which start to explode already after $10^7$ yr.

The formation of stars in the thin disk has perhaps not been continuous but rather occured in bursts.

The mass to light ratio ($M/L$ measured relative the Sun $M_S/L_S$) measures the efficiency of the Galactic material in producing light. It has been observed to be of order 3; combined with the mass-luminosity relation

$$\frac{L}{L_S} = (\frac{M}{M_S})^4 \quad and \quad \frac{M}{L} \simeq 3\frac{M_S}{L_S} \tag{4}$$

gives an average stellar mass of $\langle M \rangle = 3^{1/1-4} M_S \approx 0.7 M_S$. Considering that this is representative of the Galaxy shows that the amount of He we find — roughly 10% by number — can not have been produced in stars during the lifetime of the Galaxy ($10^{10}$ yr). It must have been produced in some other way ....

**Spiral structure, gas and dust** When mapping the location of neutral H, molecular clouds, O and B stars, H II regions, and open clusters one finds that the Milky Way displays spiral structure as do many other disk galaxies. When observed in the redder light typical of older stars the spiral structure is still discernable but less obvious. The Sun lies close to the Orion arm.

Neutral hydrogen (H I) and CO are tracers of molecular hydrogen ($H_2$). One finds that the in the region 3 – 8 kpc from the galactic center (GC) of the disk $H_2$ and cold dust dominate, H I is present in copious amounts from 3 – 25 kpc from the GC.

In the solar neighborhood the density of gas and dust is $n \simeq 0.04$ $\mathrm{M}_S/\mathrm{pc}^3$, of which 77% is neutral hydrogen, 17% is $H_2$, and ionized hydrogen 6%. The scale height of the gas disk increases with distance $R$ from the GC and is 800 pc at 12 pc. It is not only confined to the galactic plane; at far distances there is a definite warp, a feature also found in other galaxies.

There are also clouds found at high galactic latitudes, most of these appear to be falling towards the disk with velocities on the order of 400 km/s, perhaps this is gas driven away from the disk by supernova explosions and now falling back.

In addition there is a hot tenuous gas at distances of up to 50 kpc from the galaxy, and a stream of gas following the Large Magellenic Cloud (LMC), the latter perhaps a result of a near encounter between the LMC and the Milky Way.

**The Galactic Bulge** stretches out to 1 kpc from the GC, perhaps in the form of a bar (some say peanut shaped). It is difficult to see into this portion of the Galaxy from the Sun's position, but at certain locations the amount of dust is less. One such location is Baade's window in which the globular cluster NGC 6522 is visible. This globular cluster is on the other side of the GC and the line of sight to it passes within 550 pc of the GC. The stars in the bulge are both very old and very young; there is certainly ongoing star formation in the bulge. It is estimated that there are clouds totaling $10^8$ $\mathrm{M}_S$ of molecular gas in the bulge, but one also finds extremely metal poor RR Lyra stars.

**Stellar Halo** is comprised of globular clusters (there are estimated to be 230 in the galaxy, of which 110 are known) and single field stars (also known as high velocity stars). The population of globular clusters seems split in two, one older population with $[\mathrm{F}e/H] < -0.8$ and a younger one with $[\mathrm{F}e/H] > -0.8$. The latter may be associated with the thick disk.

The sum of the luminous components is on the order $9 \times 10^9$ $\mathrm{M}_S$, kinematic studies of the Galaxy seem to require more mass as we will later see.

**Dark matter halo** The total mass of the dark Galaxy should be on the order $1.9 \times 10^{11}$ $\mathrm{M}_S$within 25 kpc, which gives a total mass of $1.9 \times 10^{11}$ $\mathrm{M}_S$with a 70% dark matter fraction. It is believed that this fraction approaches 90% further out from the GC.

This material is not in the form of dim stars, brown dwarfs, black holes or other baryonic matter (MACHO's), but rather in the form of exotic weakly interacting particles (WIMP's). More on this later as we discuss cosmology.