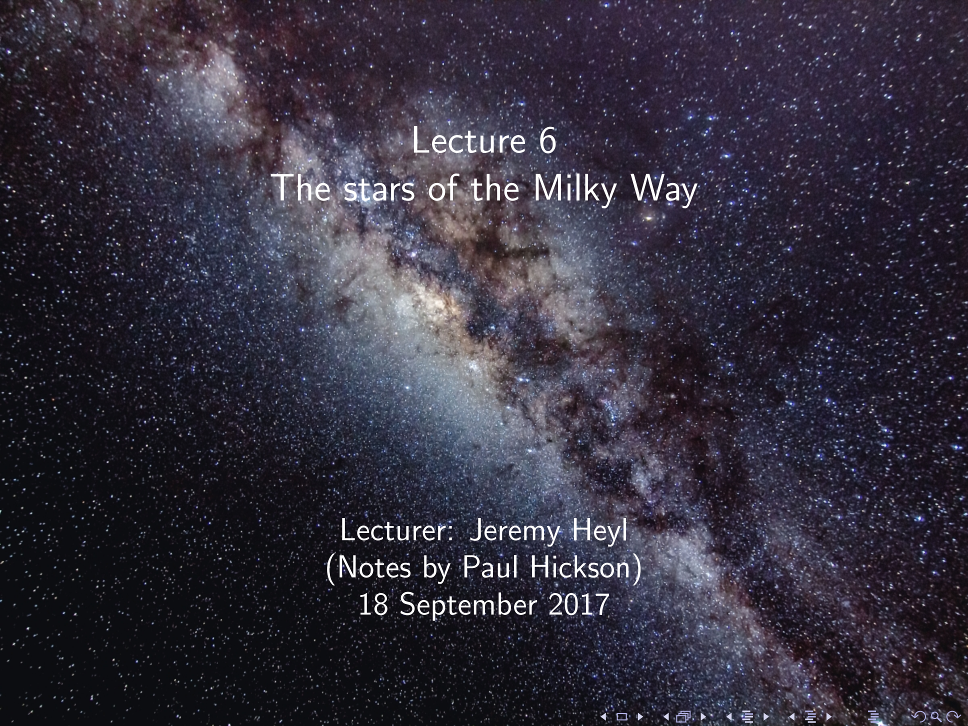


Lecture 6
The stars of the Milky Way

Lecturer: Jeremy Heyl
(Notes by Paul Hickson)
18 September 2017

Distances

Within a few hundred parsecs, parallax can be used to measure distances to stars. This will soon be extended to several tens of kpc by the Gaia satellite, which has an accuracy of about 24 uas.

Beyond this, one can estimate distances photometrically if the luminosity or absolute magnitude is known. The quantity

$$m - M = 5\log\left(\frac{d}{10\ \mathsf{pc}}\right)$$

is called the **distance modulus**

One must correct the magnitude m for extinction by interstellar dust. This is estimated from the resulting **reddening**.

Empirically, one finds that the change in colour of a star is proportional to the extinction.

$$E_{B-V} \equiv (B-V)_{\mathsf{observed}} - (B-V)_{\mathsf{true}} = A_V/R,$$

where A_V is the extinction in the V band and $R \simeq 3.1$.

Luminosity functions

As with galaxies, one can define a luminosity function for stars. $\Phi(M_\mathsf{V})\Delta M_V$ is the number of stars per pc^3 with absolute V magnitude in the range $[V, V + \Delta V]$.

In order to estimate $\Phi(M)$ from a *magnitude limited* catalogue of stars, one must correct for the fact that bright stars can be seen at greater distances than faint stars.

This can be done by dividing the number of stars in the magnitude interval by the the maximum volume at which these stars could be seen.

$$\Phi(M_V) = \frac{\text{number of stars in range } [M_V - 1/2, M_V + 1/2]}{\text{volume } V_\text{max} \text{ over which these could be seen.}}$$

$V_\text{max} =$ (solid angle covered by survey) $\times$ (maximum distance)$^3/3$.

Luminosity function for nearby stars.

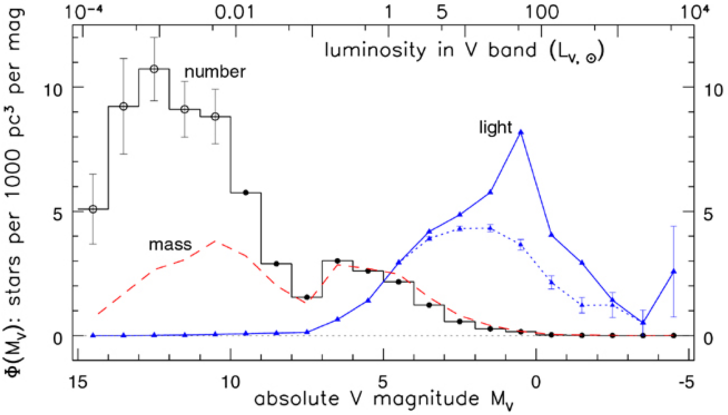


Fig 2.3 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Black: $\Phi(M_V)$, red: $M\Phi_{\mathrm{MS}}(M_V)$, blue: $L_V\Phi(M_V)$.

Luminosity function

One finds that dim stars are much more numerous that bright stars.

At visible wavelengths, most of the luminosity of our galaxy comes from A and F main-sequence stars and K giants.

At UV wavelengths the luminosity is dominated by O and B stars.

At infrared wavelengths, red stars (K and M) dominate.

Almost all the mass is in K and M dwarfs (main-sequence stars).

There are about 65 stars, totalling about $30M_{\odot}$, per 1000 pc^3.

In the vicinity of the Sun, $M/L_V \simeq 0.74$.

The mass function

The mass function $\xi(M)$ describes the distribution of stellar masses. $\xi(M)\Delta M$ is defined as the number of stars per unit volume that have mass in the range $[M, M + \Delta M]$.

Often one is interested in the **initial mass function** (IMF), which can be estimated by looking at young clusters, or by correcting the observed mass function for stellar evolution.

In the local neighbourhood, a good approximation for stars having $M > 0.5 M_\odot$ is the **Salpeter initial mass function**

$$\xi(M)\Delta M = \xi_0 \left(\frac{M}{M_\odot}\right)^{-2.35} \frac{\Delta M}{M_\odot}.$$

where ξ_0 is a constant determined by the local density of stars.

Ideally, a theory of star formation should be able to *predict* the IMF.

Mass function for the Pleiadies

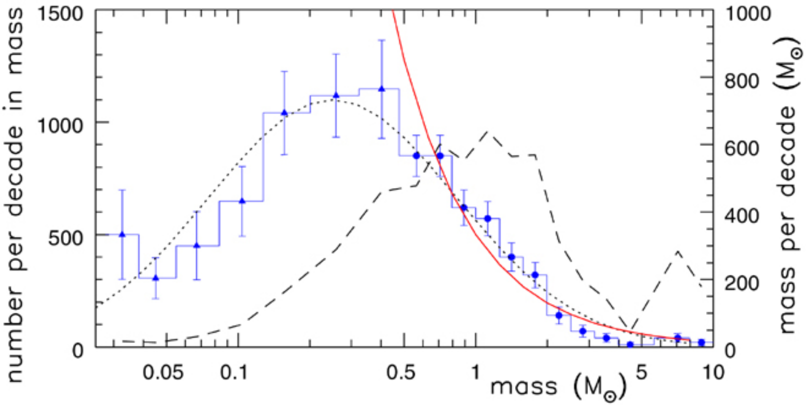


Fig 2.5 (E. Moreau) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Proper motion

Stars move as they orbit the galaxy. Because of this their apparent positions in the sky slowly change. This is called **proper motion** and is usually represented by the symbol μ (not to be confused with surface brightness).

For a given tangential velocity V_{t}, the change in the *angular* position is inversely proportional to distance,

$$\mu(\text{mas/yr}) = \frac{V_{\mathrm{t}}(\text{km/s})}{4.74\, d\, (\text{kpc})}.$$

By measuring proper motion and Doppler shift, one can determine all three components of velocity for a star.

Proper motions of stars orbiting the black hole at the centre of our galaxy can be used to estimate its distance. The result is 7.6 ± 0.3 kpc.

Spectroscopic and photometric parallaxes

Stars of the same spectral type (eg. F3V) should have about the same luminosity.

If we know the distance to a nearby star of the same spectral type, its absolute magnitude can be determined by measuring its apparent magnitude.

Now it is possible to estimate the distance to the more distant star by measuring its apparent magnitude and assuming it has the same absolute magnitude as the nearby star.

This is the principle of so called **spectroscopic parallaxes**. This generally works well for main-sequence stars, but not so well for K giants whose luminosity is nearly independent of temperature.

A variant is to measure the stars colour, instead of the spectrum, and somehow determine if it is a dwarf or a giant (for example a cool star in an open cluster will certainly be a dwarf). This is **photometric parallax**.

Structure of the disk

by measuring the luminosity function of samples of stars of a particular type in different directions and distances, one can map the density of such stars in the disk.

A reasonable model is the double exponential

$$n(R, z, S) - n(0, 0, S) \exp[-R/h_R(S)] \exp[-|z|/h_z(S)],$$

where h_R and h_z are constants, called the scale length and scale height, respectively, and $n(0, 0, S)$ is the central density of stars of type S.

One finds that $h_z \simeq 300 - 350$ pc for K dwarfs while $h_z \lesssim 200$ pc for A dwarfs. The older K stars are scattered to higher distances by gravitational encounters with massive ($\sim 10^7 M_\odot$) molecular clouds.

Typically, $h_R \simeq 2.4 - 4.5$ kpc.

Vertical distribution of stars in the disk

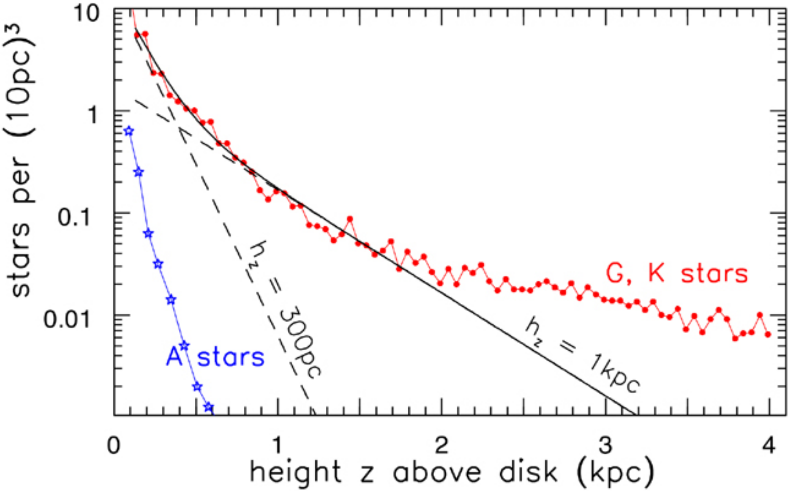


Fig 2.8 (Reid, Knude) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The thick disk

The excess K dwarfs at $z \gtrsim 400$ pc belong to the thick disk.

The number of thick disk stars per square parsec at a given value of R is about 30% of the number of think disk stars.

Since the thick disk contains no O, B or A stars it must be older than ~ 3 Gyr.

Stars in the thick disk have low metal abundance, typically $10 - 50\%$ of the solar abundance.

They also have higher **velocity dispersion** $(\sigma_R, \sigma_\phi, \sigma_z)$ than thin-disk stars, and lower azimuthal velocity v_ϕ than the Sun.

$$\sigma_j \equiv \sqrt{\langle (v_j - \langle v_j \rangle)^2 \rangle}, \qquad j = R, \phi, z.$$

Open clusters

Fig 2.11 (NOAO) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Open clusters

Open clusters (also called galactic clusters) are young associations of typically several hundred stars that formed together from the collapse of a gas cloud.

Their distances, and ages can be estimated by **main sequence fitting**. This technique involves fitting the observed colour-magnitude diagram (CMD) of the cluster to theoretical models, with distance and age as free parameters.

Their ages rarely exceed 1 Gyr and most are < 300 Myr.

Older clusters are found to have a larger scale height ($H_z \simeq 375$ pc).

There is a wide range of metalicities. Clusters further from the galactic centre are more likely to be metal-poor.

CMD of the Pleiades cluster

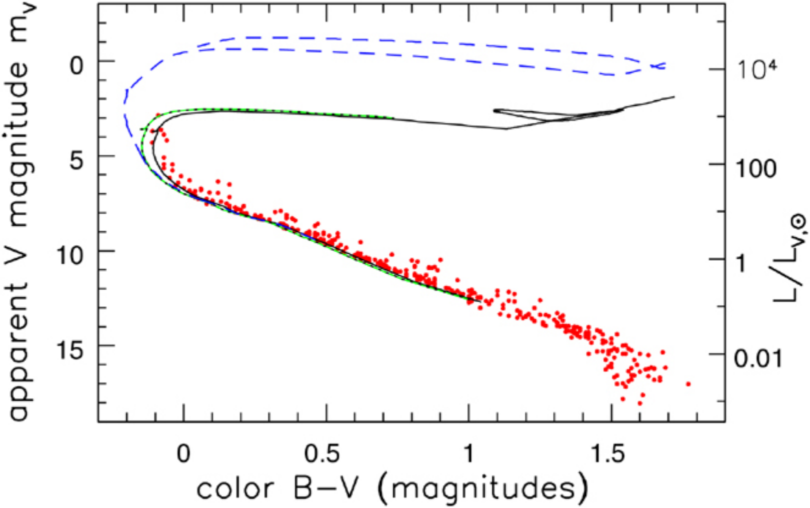


Fig 2.12 (J.-C. Mermilliod) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Note dots just above the main sequence. These are binary stars.

Globular clusters

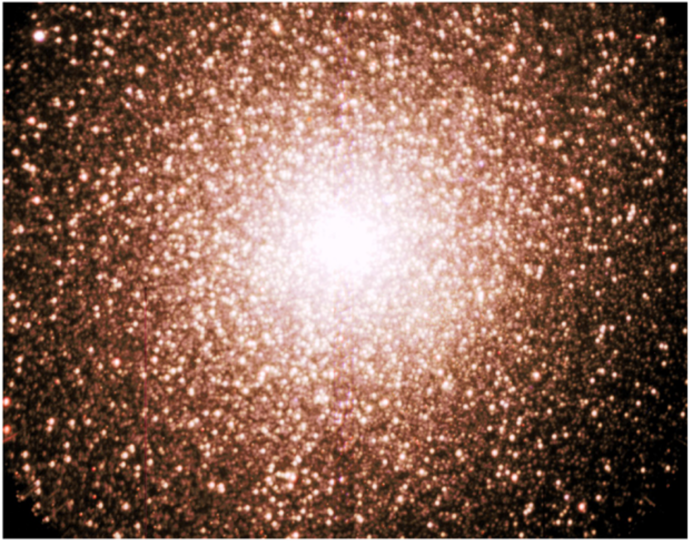


Fig 2.13 (SALT) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Globular clusters

Globular clusters are dense spherical systems of $10^4 - 10^6$ stars. The Milky-Way has about 150 of them.

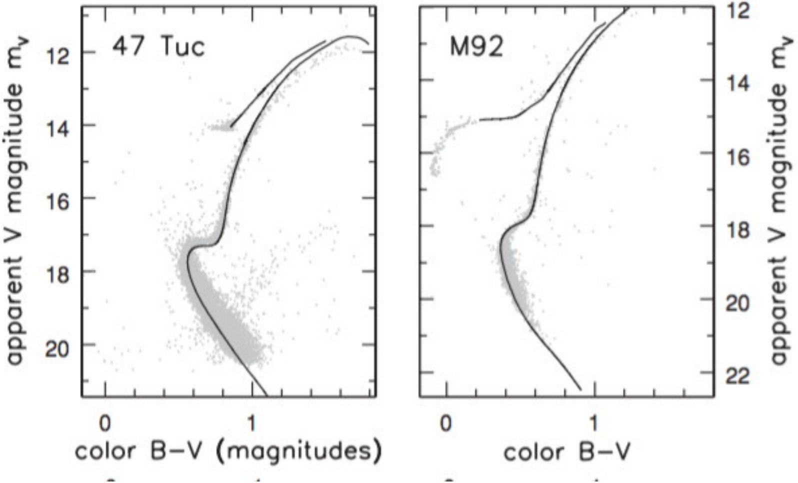
The central core has a typical radius $r_c \simeq 5$ pc, and the outermost stars may extend to $r_t \simeq 30$ pc, where the tidal force of the galaxy pulls them from the cluster.

Most are very old, 10 Gyr or more. Their CMD has well-populated giant and horizontal branches.

Distances can be estimated by main-sequence fitting, and also from RR-lyrae stars.

RR-Lyrae's are low mass stars on the horizontal branch that vary with periods of $0.1 - 1$ day. They all have about the same luminosity $L \simeq 50 L_\odot$.

Globular clusters



The halo

The **halo** consists of a population of old stars, globular clusters and isloated gas clouds.

These have likely been accumulated as a result of cannibalism. If a small galaxy passes near the Milky Way, it looses kinetic energy and can spiral in.

The small galaxy is then pulled apart by tidal forces and assimilated into the halo.

We can recognize this by finding groups of stars in the halo that follow a common orbit. These are called "streams".

The latest victim is the Saggitarius dwarf galaxy.

Stars in the halo have random velocities and do not systematically rotate like the disk.

Colours of stars in the direction of the NGP

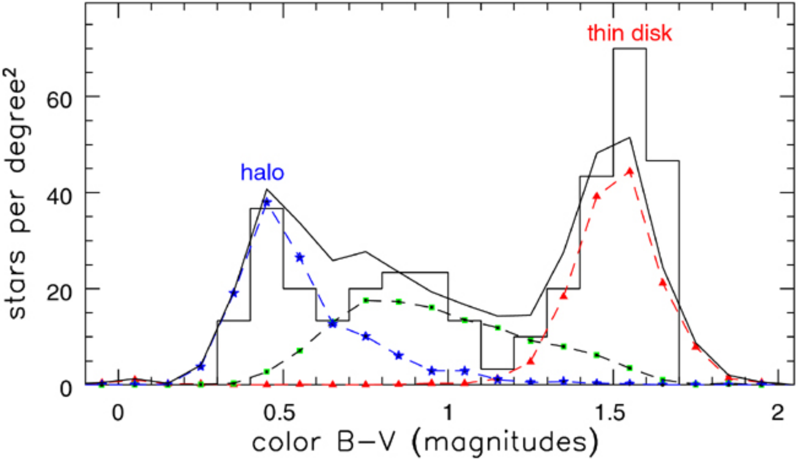


Fig 2.16 (N. Reid) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Low-metalicity stars tend to be blue.

The bulge and nucleus

Stars in the bulge form a population that is distinct from the halo. These stars are not as metal-poor as halo stars.

The average rotation speed in the bulge is about 100 km/s, slower that of the disk, and the stars have greater random velocities.

The nucleus contains a dense star cluster, surrounded by a torus containing $10^6 M_\odot$ of molecular gas.

The nuclear star cluster has a very high density, $3 \times 10^7 M_\odot$ pc^{-13} within 1 arcsec (0.04 pc), and is actively forming stars.

Infrared imaging using adaptive optics reveals the motion of these stars, and the presence of a black hole with a mass of about $4.5 \times 10^6 M_\odot$.