STELLAR ASTROPHYSICS

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Chapter 1

Color-Magnitude Diagram

1.1 Stellar Population

We have different kinds of stellar population in the universe. We can start by dividing the totality of stars into two macrocategories: resolved and unresolved stellar populations.

Resolved stellar population This is a concept that depends on the observational tool we have, so whether we use a high-resolution telescope. A resolved stellar population is a population of stars where we can distinguish one star from another. For this population we can measure the luminosity of single stars (using photometry) and we can infer the chemical composition and chemical abundances of single stars (using spectroscopy).

Unresolved stellar population We cannot resolve the light of single stars so we need to use the integrated light in order to get info on the galaxies. In the distant universe, we cannot get information about an unresolved stellar population unless we know the properties of stellar population from resolved stars. Thus we need to know the properties of stars from resolved photometry and spectroscoy to understand the integrated properties of light from distant GCs.

Reminder

- **Luminosity (L)**: intrinsic property of an object. Total amount of electromagnetic energy emitted by a star per unit time. Measured in [J/s, W]
- **Observed Flux (or Apparent Brightness)**: is the power per unit area that we receive from a star. Measured in [W/m^2]. It can be computed as $F = L/4\pi d^2$.
- **Apparent Magnitude**: logarithmic measurement of the apparent brightness. Is not luminosity: a star can exhibit a faint (high in module) apparent magnitude because it is far from us.

Simple Stellar Population - SSP It is an assembly of coeval and chemically homogeneous stars. It is described by some parameters:

1. Age
2. Chemical Composition
3. Initial Mass Function (IMF): number of stars per interval of mass after the formation of the stellar population. Very difficult to derive because for very high redshift we observe the present day function so the IMF after 13 Gyr of stellar and dynamical evolution.

Complex Stellar Population It is the opposite of SSP. If one or more of the properties of SSP are not fulfilled then then the stellar population we are analyzing is a CSP and it is composed by various SSPs.

1.2 Clusters

Globular Clusters Historically globular clusters were considered the best examples of SSPs in nature. They are ancient stellar systems from which we can infer the properties of stars and SSPs since they are populated by up to millions of old stars.
They are mostly present in the halo of Milky Way but they also populate the internal part of the Galaxy (bulge) and they are present even in the galactic disk. The stars inside a GC are tightly bounded by gravity which gives them their spherical shape and relative high stellar density toward their center. They are old and relatively low mass and their density, which depends on radial distance, increases toward the center.

Open Clusters Open clusters were considered the best example of young simple stellar population in nature. We can find them surrounded by the cloud that once formed the cluster itself. Open clusters are a collection of a small number of stars weakly gravitationally bound that were formed by the same molecular cloud. Usually they populate the disk of the galaxy and they can dissolve after a few hundreds Myr depending on their mass, density and other parameters.

Stellar population I and II There is not a sharp definition between open and globular clusters but we know that GCs host population II stars (old and metal poor) while open clusters host population I stars (young and metal rich). There may exist even population III stars but they have never been discovered: they do not contain any metal and have the same composition of the material after the Big Bang so a high content of hydrogen and helium and a tiny amount of lithium.

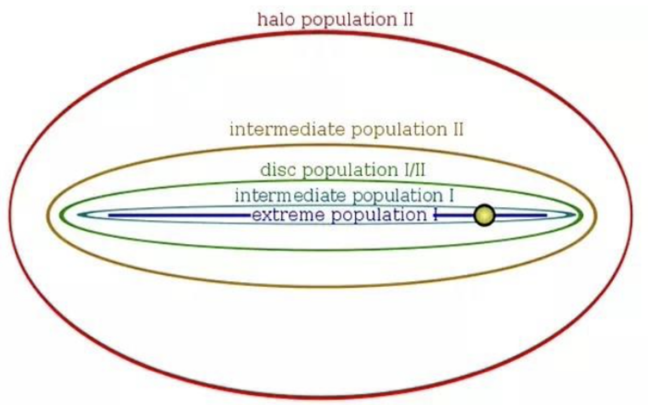


Figure 1.1: Simplification of the structure of our galaxy. In the disk we have extreme (very young) population I. Moving at higher latitude we have a mix of very young pop I and intermediate pop I, then we have a transition from pop I to pop II . In the halo nearly all the stars are pop II.

Stars in a cluster

Stars in a cluster have the following characteristics:

1. different colors depending on their temperature;
2. different luminosity, dimensions;
3. share the same distance so the apparent brightness corresponds to the intrinsic luminosity.

1.3 The Color-Magnitude Diagram

The CMD is a plot of the stars' magnitude (luminosity) as a function of their color (proxy of the temperature). The color od a star is the difference between two magnitudes, blue means hot and red means cold. The sequence in which the stars are located is related to their evolution.

In the CMD of a young cluster, like the ones in Fig. 1.2b is very difficult to determine which stars belong to the cluster and which belong to the external field. To do so we can now use GAIA using proper motions because stars in a cluster have a common motion in the plane of the sky together with the radial velocity that provides the velocity of the stars along the line of sight. Stars within a cluster have random motions but considering the whole cluster they have a common motion.

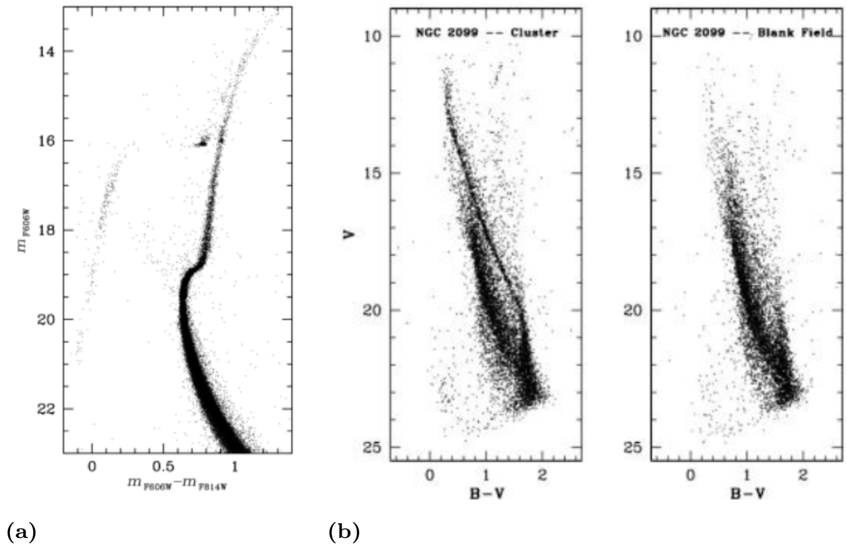


Figure 1.2: In Fig. 1.2a we can see the CMD of an old cluster while in Fig. 1.2b we have the CMD of a young cluster.

Magellanic Clouds To study clusters that are far away we use statistic decontamination. We use the stellar proper motion: stars in a cluster have different motion with respect to the surrounding field. To quantify it we use the vector-point diagram of proper motion: on the x-axis we have the motion in the direction of the right ascension while in the y-axis we have the direction along the direction of the declination. We see that stars are not randomly distributed but they form two main blobs of stars: one where the velocity dispersion is small and one where it is high. Using this is easy to determine which stars belong to the cluster and which not.

How do we construct the CMD? Observationally we solve stars in colors and then we sort them in luminosity. In this way bright stars are in the upper part of the CMD and faint ones are in the lower part.

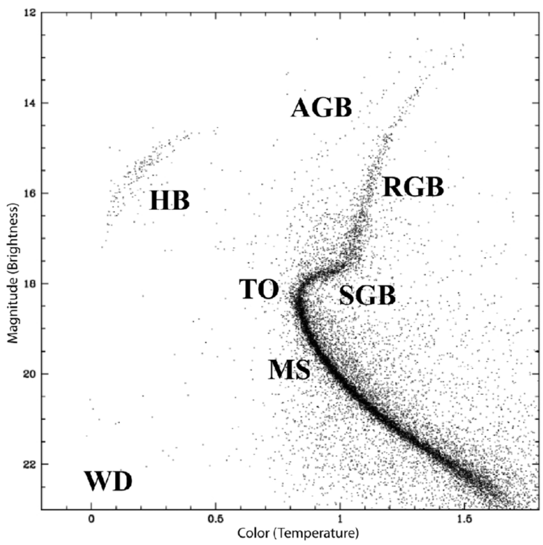


Figure 1.3: Evolutionary phases and branches in a CMD.

Main sequence stars are similar to the Sun and burn hydrogen in the core. Stars in the sub giant branch are evolving into the red giant branch where they have different processes to produce luminosity. Stars in the horizontal branch produce energy in the core by burning helium. Lastly we have the white dwarf cooling sequence.
By looking at the CMD we can get which stars are in which evolutionary phase but we can also get the age of the stellar population by looking at the turn-off point. Younger clusters have a bluer turn-off point, while if the cluster is older then the turn-off point gets fainter and redder. The turn-off tells us when a star has finished the hydrogen in its core and starts burning hydrogen in the shell.
Using the CMD we can also infer the presence of binary systems, multiple stellar populations and the chemical composition of single stars (and doing so information about the primordial cloud that originated the cluster at high redshift.)

1.3.1 Reading the CMD

In a CMD we have stars in all evolutionary stages and we know that stars evolve in different ways and time depending on their mass. To investigate the way they evolve we need to use theoretical tools.

Stellar tracks The stellar evolutionary track is the curve in the CMD representing how the color and luminosity of a star change with time. In the theoretical plane we have luminosity against effective temperature. In Fig. 1.4 we can see different stellar tracks depending on the mass of the stars. Because of the different masses they spend a different amount of time in each evolutionary stage. Stars with low masses need more time to evolve while high mass stars evolve faster. This track indicates how the luminosity/color of stars changes with time. We can't see this by just looking at the sky since in the sky we observe a collection of stars in different evolutionary stages that have born all at the same time.

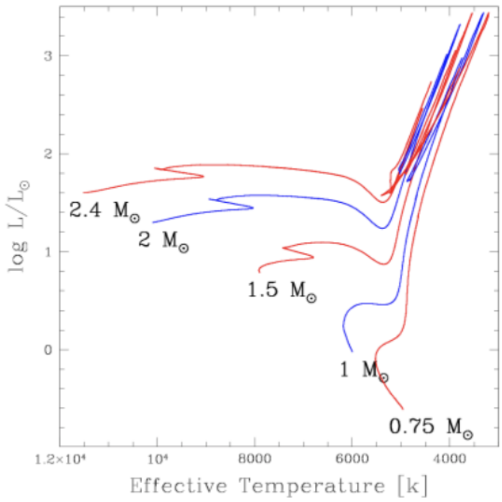


Figure 1.4: Stellar tracks for different initial masses.

Isochrones Stellar isochrones are the curves in the CMD which represents stars with the same age. The shape of the isochrone for fixed chemical composition and fixed distance changes depending on the age of the stellar population. The point more sensitive to the age variation is the turn-off point, where the stars leave the main sequence, so it is the main chronometer provided by stellar evolution. When we are dealing with old stellar population, the turn-off point becomes fainter and colder. Moreover we have some changes in other parts of the CMD, like the position of the subgiant branch.

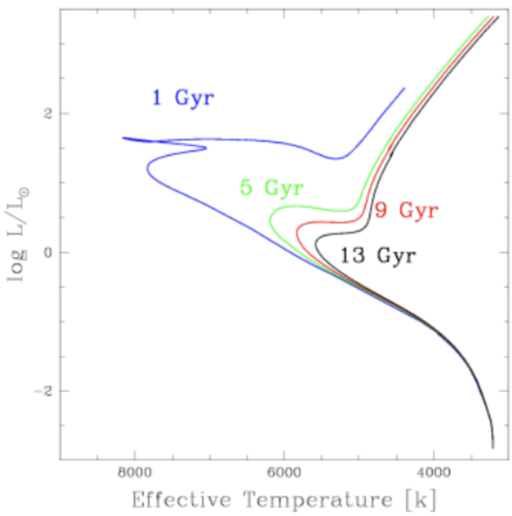


Figure 1.5: Isochrones for different ages. This is a theoretical plot (luminosity vs temperature), quantities that cannot be observed directly from the telescope. Observations provide the magnitude in different filters whereas the theory provides evolutionary time, luminosity and effective temperature.

From theory to observations

We have some relation that connect the observed properties of stars with the ones predicted by stellar models.

Bolometric magnitude Measures the total radiation of a star emitted across all wavelengths of the electromagnetic spectrum. The bolometric magnitude of the Sun $M_{bol,\odot}$ is constant and its value is 4.74 $L_\odot$ is used to normalize the luminosity wrt the Sun. The bolometric magnitude is indicative to the total radiation of the star. We cannot derive it from the observations since telescopes are set on narrow windows of the spectrum. We observe the magnitude in a given filter.

Absolute magnitude Is the magnitude in a given photometric band at a unit distance of 10 pc, so is not what we observe since we observe the apparent magnitude. It is related to the bolometric magnitude as:

$$M_A = M_{bol} - BC_A$$

where BC_A is the bolometric correction in the photometric band A. It depends on the filter we are using.

Apparent magnitude It is related to the absolute magnitude as:

$$m_A = M_A + 5\log(d) - 5 + A_A$$

where A_A is the interstellar extinction in the band A. This extinction depends on the filter we are using: in the UV we have a lot of absorption while in the IR the amount of absorbed light is much smaller.

K correction When dealing with high-redshift objects we must account for the fact that the redshifted spectrum is stretched through the bandwidth of the filter and so the light we observe comes from a bluer part of the spectral energy distribution because of the redshift. We need to use a correction that accounts for this phenomenon, which is the K correction that depends on the filter transmission, on the flux of the source and on the reddening.

1.4 Structure and radiation of a star

The majority of stars appears as point-like sources so on the detector we have the point spread function (PSF). For close stars and bigger ones we can resolve its surface using interferometers. To study the stars we have to study the Sun. Its outer part is the photosphere and it is the one we see when we look at it. Going to the center we have the convective zone, the radiative one and the core where the temperature reaches $15 \cdot 10^6$ K and we have hydrogen burning.
In first approximation it is a black body. This is due to the fact that the light we received from a star has been released from the photosphere where the optical depth τ is about 1. The optical depth is the probability that a photon has an interaction with stellar matter and is given by:

$$\tau = \int_r^\infty \kappa_{rad}\, \rho\, dr \tag{1.1}$$

The light emitted by a star is characterized by the black body spectrum whose energy distribution depends only on the effective temperature. Black body radiation is described by the Planck law:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT} - 1} \tag{1.2}$$

and the total flux is then $f = \sigma T^4$. The energy distribution depends only on the effective temperature of the star that can be inferred using the **color index**.

Color indexes Color indexes provide a measure of the slope of the black body curve, and therefore the temperature. A generic color index is defined as the difference of the magnitudes in two different photometric filters. Dealing with colors has some advantages like the fact that we don't have to deal with distances, but it also have disadvantages like the fact that it is affected by extinction:

$$(A-B)_0 = M_A - M_B = m_A - 5\log(d) + 5 - A_A - m_B + 5\log(d) - 5 + A_B = (A-B) - (A_A - A_B) = (A-B) - E(A-B) \tag{1.3}$$

where $E(A-B)$ is the color excess, or reddening.

In reality we don't have a perfect black body function because we have absorption lines due to the stellar atmosphere where $\tau < 1$ which induces a dependence of the spectral energy distribution on the properties of the star like the gravity and the chemical composition. We have to compare observations with theoretical models of the stellar atmosphere to study the stellar spectrum and compute the correct bolometric correction to any given filter of our telescope.

Absorption Indicates that there is matter between us and the observed object. The absorption is not the same in the whole sky: in the galactic plane is very strong while looking at the poles is almost negligible. This phenomenon is responsible for the broadening of the CMD (real ones are more broadened than theoretical ones).

Extinction The interstellar space is permeated by the interstellar medium, composed by gas and dust, which is responsible for scattering the radiation.
The observed flux is related to the intrinsic one, in case of no absorption by:

$$f_2(\lambda) = f_1(\lambda)e^{-\tau_\lambda} \tag{1.4}$$

where τ_λ is the optical depth of the ISM. Extinction is not uniform along the spectra since it varies as λ^{-1} in the optical part of the spectrum. It is dramatic for short wavelength, but is less serious in the NIR. The extinction at wavelength λ is $A_\lambda = 1.086\,\tau_\lambda$.

1.5 The formation of the Galaxy: constraints from the CMD

Lambda Cold Dark Matter model The Universe is characterized by a cosmological constant Λ, associated to dark energy and cold dark matter. Predictions from the ΛCDM model are in agreement with:

- existence and structure of the cosmic microwave background (the universe is not uniform in the microwave range);
- accelerating expansion of the universe;
- abundances of hydrogen, helium and lithium, which are produced in the early phases of the formation of the universe;
- distribution of galaxies on the large scale, the density decreases as we go outside the filaments.

This is a good model but has some problems. Simulations based on the ΛCDM model predict that dark matter clusters hierarchically so we expect and increasing number of smaller size dark matter halos. In contrast with what predicted by this model the number of dwarf galaxies is orders of magnitude lower than what we expect. To solve this problem, called the **missing satellite problem** we have to constrain the galaxy formation using the CMD.

To try answer to this question we have to use theoretical models, observations, stellar isochrones and CMDs of globular clusters. This work has been done by Muratov and Gnedin who built a plot that shows the age of families of globular clusters against metallicity. We have to compare this theoretical plot with the observations.

1.5.1 Metallicity

Another important parameters is the metallicity. To measure it we have to take some elements as proxy of metallicity, like the iron. Iron abundance can be defined in different ways. The traditional metal-abundance indicator is the quantity:

$$[Fe/H] = \log(N(Fe)/N(H))_\star - \log(N(Fe)/N(H))_\odot \tag{1.5}$$

If ones assumes the distribution of heavy elements that we see in the Sun as universal the conversion from [Fe/H] to Z is given by:

$$[Fe/H] = \log\left(\frac{Z}{X}\right)_\star - \log\left(\frac{Z}{X}\right)_\odot$$

Using the empirical value of the solar ratio we get:

$$[Fe/H] = \log\left(\frac{Z}{X}\right)_\star + 1.61$$

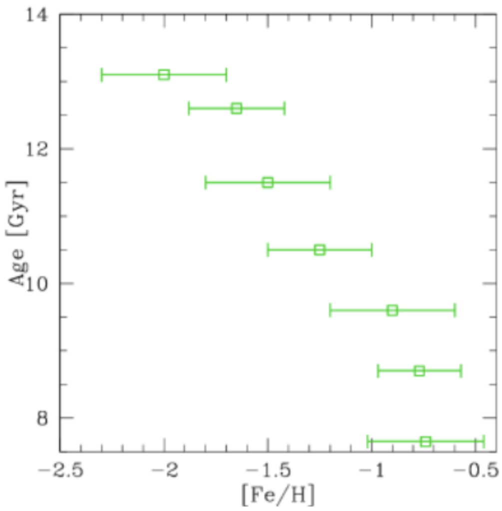


Figure 1.6: Muratov and Gnedin, age of clusters vs metallicity.

For definition $[Fe/H]$ of the Sun is zero.

In isochrones we can easily see the difference between metal-rich and metal-poor populations: metal-rich are redder and fainter than metal-poor of the same age. Moreover the red giant branch shows different inclinations for different metallicity: metal-poor star's red giant branch is more vertical while the metal rich one tends to be more horizontal. The turning point depends not only on age but also on metallicity. We can constrain the metallicity of

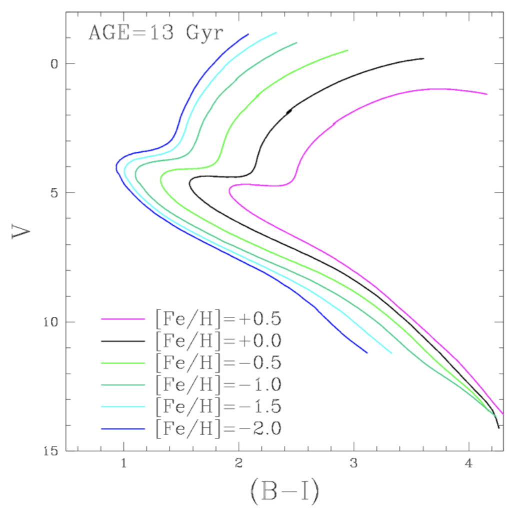


Figure 1.7: Isochrones of populations with different metallicities.

the stellar population by looking at the slope of the red giant branch. Once we know the metallicity we can derive the age of the stellar population.

1.5.2 Age determination

To infer the age of a GC, which could provide lower limits to the age of the universe, we first select the isochrones then we adopt the iron abundance fixing it and solving the fit only for the age. We have other parameters such as the distance so if we want to put isochrones on top od the CMD we need first to derive the distance and then the reddening. So to compare observations of a stellar population with isochrones we need to solve for age, distance and reddening. Then we derive the values of age, distance and reddening that provide the best fit between the isochrones and the observed CMD.

All age determination is model dependent and we can infer the age using different techniques and then comparing them. We have to see if the ages derived using different techniques coincide with each other.

Age-metallicity relation Clusters with different distandces from the Galactic Center follow different age-metallicity relations. We can divide clusters in two main families: clusters within 8 kpc from the center of the galaxy and cluster further away 8 kpc. By looking at the plot in Fig. 1.8 we can see that there is a different behavior between the two

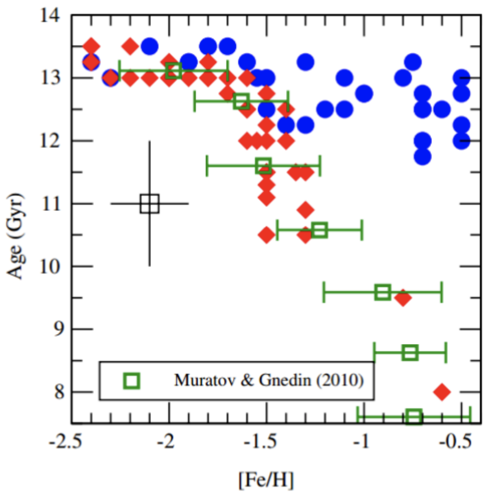


Figure 1.8: Red clusters are the ones within 8 kpc from the galactic center while blue ones are the ones further away.

categories of clusters. These results indicate a rapid chemical enrichment in the inner galaxy and suggest prolonged GCs formation in the outer halo. Comparing the observational data (red and blue points), with the theoretical prediction (green bars) we see a good match for what regards the red clusters which confirms the ΛCDM scenario. If we look at the closer clusters we see that there are discrepancies since in this case we have a rapid change in metallicity, a fast enhancement in Fe/H not expected by the ΛCDM model. This suggests that we could have had a prolonged globular cluster formation in the outer halo.

Relative age of stellar populations: the vertical method This is an alternative approach to derive the age of stellar populations. It allows us to find the relative age of GCs and it is based on the magnitude difference between the main sequence turn off and the luminosity of the horizontal branch at the level of the RR Lyrae instability strip. This magnitude difference depends on the stellar age. The position of the horizontal branch is almost always the same, while the position of the turn off decreases as the stellar population gets older.
Why does the HB remain constant? This is due to the fact that the helium core mass at the He-burning ignition is almost constant so since for a fixed metallicity the luminosity of the HB depends on the mass of the helium core, it is almost constant.

Advantages and disadvantages of the vertical method

Advantages

- not dependent on cluster distance (these are relative measurements);
- not dependent on cluster extinction (uncertainty on reddening is reduced);
- not dependent on photometric calibration;
- solid from the theoretical point of view.

Disadvantages

- accurate determination of the turn off luminosity can be challenging;
- accurate determination of the HB level is challenging in clusters with a few or no RR Lyrae;
- the HB luminosity is dependent on the helium abundance: when dealing with multiple stellar populations may have different helium content;
- the HB is not really horizontal in the various bands: the vertical method can be used only in the V band, in which the HB is effectively horizontal at the level of the RR Lyrae

1.6 The missing satellite problem

In contrast with the ΛCDM model, the number of dwarf galaxies is orders of magnitude lower than the one expected from simulations. The satellites we are talking about are satellites of dark matter which are associated to dwarf galaxies.
Let's start by analyzing two phenomena in the early universe that involve hydrogen: the recombination and reionization.

Recombination (Z=1000) The universe became transparent, after being opaque due to scatter of photons and free electrons. Electron and protons recombined to form neutral hydrogen, the dark age started: there was nothing able to produce light. After this, we have the reionization.

Reionization (Z=20-6) Some unknown objects formed (population III stars?) and started to radiate energy. The universe was a ionized plasma once again. The universe, which was full of low-density ionized hydrogen, remained transparent. Reionization is associated to energy sources that produced high energy photons and possible investigations of the ΛCMD model. After the reionization the universe kept to be transparent till now.
During these phenomena there were galaxies made of dark matter that started forming stars but at the age of reionization the photons shut down the star formation. So we have dark matter clumps that never formed stars. We can identify three different types of dark matter clumps: the ones that formed stars, the ones that did not and the ones with low star formation that stopped after reionization. Let's focus on bright and low-luminosity dwarf galaxies. Dwarf galaxies could have followed one of three different evolutionary paths:

- **True fossils** - formed most of their stars prior to reionization
- **Polluted fossils** - star formation continued beyond reionization but at lower pace
- **Survivors** - largely formed their stars after the age of reionization

We can study these objects using for example the SDSS. This survey observed the background sky, which is not uniform because of the presence in the halo of the galaxies of a large number of satellites. These satellites can be globular clusters, dwarf galaxies, but can also be stellar streams distributed on a large area of the sky not known before. The main stream is the Saggitarius stream, that can be used to investigate the quantity of dark matter. The SDSS also discovered another kind of galaxies: the Ultra-Faint Dwarfs, which are galaxies with a lot of dark matter. Are these galaxies true fossils? To determine this we have to measure their age: if the stars are younger than the age of the reionization then they are true fossils. After some research we know that 80% of their stars formed by z=6 and the totality of their stars formed by z=3. This suggest that the star formation in the smallest dark-matter sub-halos was suppressed by a global outside influence (e.g. reionization). So they are made by the pristine material that was already polluted by population III stars ejecta but is still a metal poor material. The age of the stars of UFD confirm the theory where we suggested that some dark matter halos are not able to form stars, while there are other dark matter halos that survived and still form stars.

1.7 Unresolved binaries

Unresolved binaries are binary systems that will appear as a single point-like source with magnitude given by (remember: fluxes sum, magnitudes no):

$$m_{bin} = m_1 - 2.5 \log \left(1 + \frac{F_1}{F_2}\right) \tag{1.6}$$

This formula is valid for every binary system but if the two stars are in different evolutionary stages the color of the unresolved binary will be dramatically different. For example if we have an MS star and a WD the binary will be a little brighter than the brightest star.
Using this formula we have the information to calculate the position of the binary system in the CMD. Let's consider some different cases:

1. **Equal mass binaries** ($F_1/F_2 = 1$). The resulting magnitude for the binary system is then $m_{bin} = m_1 - 0.752$ so the binary system will appear as a single point 0.752 mag brighter than each single star and its collor will be the same as the one of the two components. If in a stellar population we consider binary systems, their position on the CMD is on a line parallel to the main sequence. If we decrease the mass ratio the binary system will shift towards the original one (Fig. 1.9, equal mass binaries are the ones with $q = 1$).

2. **Simple stellar population**. Stars are distributed in the CMD diagram, the fluxes are related to the stellar masses, as a consequence the luminosity of the binary system will depend on the mass ratio $q = M_1/M_2$. In this case we assume $M_1 \geq M_2$, so $0 \leq q \leq 1$.

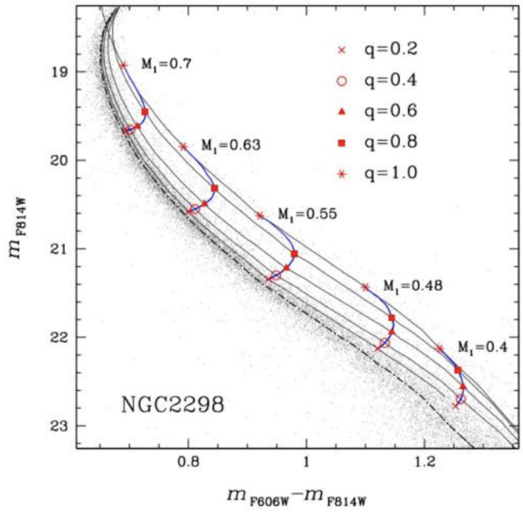


Figure 1.9: Curves described by binaries systems with different mass ratio.

How do we move from mass to luminosity? We need mass to luminosity relations provided by the isochrones. Knowing the mass and the luminosity of the first star we can simply derive the mass of the second star using the mass ratio and then we move to the isochrones and by using the mass luminosity ratio we derive the luminosity of the second star.

Each component of the binary system evolve in an independent way, since they are connected only from a gravitational point of view and they do not exchange mass. Sometimes we may have binary systems that exchange mass and are responsible for strange phenomena.

1.8 White Drawfs

White dwarfs are the evolutionary end stage of more than 95% of the stars. WDs are dying stars, stellar core remnants composed mostly by electron degenerate matter. They are the final stage of stars with masses smaller than 8-10 $M_\odot$ (bigger stars explode in SN). The core temperature of 8-10 $M_\odot$ stars fuses C but not Ne hence a O-Mg-Ne dwarf may form. Stars with very low mass, on the contrary, can't burn helium so a He white dwarf will form.

White Dwarfs Cooling Sequence The evolution of a WD is a cooling process with a strong age-luminosity relation. The distribution of stars in the WDCS changes depending on the age, in particular the bulk of stars becomes fainter and redder when the stellar population becomes older. We can use, in order to make a comparison, the luminosity function which refers to the counting of stars in a given interval of luminosity. By increasing the age, the luminosity function changes: for old stellar population the peak is shifted to fainter magnitudes so we need to get very precise luminosity determination for very faint stars. So the separation in magnitude for a fixed age become smaller when the stars become older. This is a powerful tool to derive the age but it becomes challenging when dealing with old stellar population because the peak separation gets smaller and the luminosity of the stars becomes fainter.

But why do we care so much about inferring the age of a stellar population using the WDs cooling sequence, even though this means dealing with very faint stars? Because the method to derive the age using the turn off point and the HB is based on a certain physics (stars that burn material to produce luminosity), while WDs follows a completely different physics. Moreover while the position of the MS and the HB depends on the metallicity of the stellar population, the position of the WDCS is always the same even for different metallicities. These two are independent methods that can be used to verify if our work is valid or not.

The WD age determination confirms in many cases the MS age determination, confirming that metal rich and metal poor clusters formed in different epoch.
What about the possibility that the age derived from the turn off point is not correct? This could be due to uncertainties in our modeling of hydrogen burning stars. This is the reason why we want to investigate the WD cooling sequence in GCs. The main challenging point is that in the closest GCs the WDCS approaches very faint magnitudes so it takes a long observational time.

The strange case of NGC 6791

NGC 6791 is a 8 Gyr old (using MS turn off) galactic open cluster (even though it looks like a globular cluster) that does not exhibit evidence of multiple stellar population. It is characterized by high metallicity. It is quite close so it easy to use it as a test to derive ages from WDCS. When measuring the age with this method we find that the age of the cluster is 2.5 Gyr. The possible consequences are: either age inferred from MS turnoff or from WDCS, or both, are wrong or there exist an exotic population of pure-helium WD.

Using other data from HST the white dwarf cooling sequence reveals a second peak in the WDCS luminosity function: there are two populations of pure-He WDs and classic WDs?
No, this is due to **unresolved binaries**. To estimate the fraction of binaries in a stellar population we have to take the ratio between the number of stars in the binaries region and the total number of stars.

We know that binaries are distributed on the right side of the main sequence and that their position depends on the mass ratio and that if we fix the mass of the primary star and we increase the mass ratio the binary system will appear redder and brighter than the primary star, following the blue line (Fig. 1.9) and it will approach the star symbol where the two components of the binary system have the same mass. In this case the binary will appear as a point-like source with exactly the same color as each single component but 0.752 mag brighter.
We can infer the fraction of binaries of SSP because they are redder and brighter than the main sequence but we have to be aware of errors due to the observations and to the fact that if a binary has a very low mass ratio the position of the binary system is very close to the fiducial line. This means that we are able to detect only binary systems whose mass ratio is $q \geq 0.5$.

Chapter 2

Stellar Spectroscopy

Spectroscopy is used to infer the chemical composition of stars by spreading the light in term of wavelength an analyzing the flux in terms of the wavelength. From spectra we can get chemical composition, effective temperature and gravity of stars. Photometry, on the other hand is used to investigate the integrated light over all or a given range of wavelengths. These two methods goes together because they are complementary. The main advantage of spectroscopy with respect to photometry is that we have a detailed analysis of the spectrum in a small region allowing us to see the features of the spectra and study its details. On the other side since we need to spread out the light we have limitations in terms of stellar luminosity because when we spread out the light we reduce the signal to noise for each pixel of the CCD, so we are limited to bright stars, while with photometry we can approach even fainter stars.

Spectroscopy is the study of stellar atmosphere which is the most important source of radiation in the universe. They are an unique window on stellar interiors and their spectra contain a fossil record of the history of the cosmos.

Line formation A cool thin gas seen in front of a hot source produces absorption lines. In the continuum region the optical depth τ (probability of a photon to interact with matter) is low and we see primarily the background. At the wavelengths of spectral lines τ is bigger and we see the intensity characteristic of the temperature of the cool gas. Since the temperature of the stellar atmosphere is lower than the central temperature of the star, in the stellar spectrum we see mostly absorption lines. We can eventually have emission lines but those regards phenomena produced in the disk around the star. To quantify the level of the continuum and the depth of the lines we plot the intensity as a function of the wavelength.

From a stellar spectrum we can extract the star's ID so its spectral type and photometric classification, and the photometric parameters such as effective temperature, metallicity and gravity.

2.1 Abundance scales

When we describe a star we talk about the abundance of three components: hydrogen (X), helium (Y) and metals (Z), using the mass fraction. We can use different scales to define the abundance:

- **12 scale**:
$$\log \varepsilon(X) = \log(n_X/n_H) + 12(\log \varepsilon(H) \equiv 12)$$
- **[ ] scale**:
$$[X/H] = \log(n_X/n_H)_\star - \log(n_X/n_H)_\odot$$

For definition we have that $[X/H]_\odot = 0$, so if this number is bigger than zero we have super-solar abundances and vice-versa.

2.2 Line broadening

Each line is characterized by three main components:

1. **Natural width**: the line is not a Dirac delta, it is a broaden line. Its profile is Lorentzian and very narrow due to the Heisenberg uncertainty principle ($\Delta E \Delta t = h/2\pi$). The transition between two identical levels in two identical atoms can produce photons with slightly different energies. For these reasons spectral lines are not infinitesimal in wavelength but exhibit a certain width described by the Lorentz function.

2. **Pressure width**: due to collisions between particles, mostly affect the shape of the wings of the spectral lines.
3. **Thermal (or Doppler) width**: due to the thermal motion of particles. It follows a Maxwell-Boltzmann distribution.

There are other phenomena that contributes to the broadening of the lines like the **Zeeman effect**, which affects atoms in strong magnetic fields and splits the lines into multiple componentµs depending on the strength of the magnetic field.

Another kind of broadening is the one due to stellar rotation. Not rotating stars have more narrow lines than rotating stars. Different part of the star are characterized by the different rotational velocity and for this reason different broadening.

2.3 Different kind of lines

Hydrogen lines We have the Lyman (n=1) series, the Balmer (n=2) and Paschen (n=3) transitions respectively in the UV, the Optical and the IR region.

Helium lines This is the second most-abundant element in stars, very difficult to be detected in stars because helium lines visible only in very hot stars like O-B stars. Not visible in stars like the Sun. Visible only in stars in a small region of the CMD, not in the whole horizontal branch. In very hot stars we can see the helium lines but we may have some events of sedimentation but the helium abundance inferred is not the right helium abundance of the star. Helium stars are very weak, we have to use very powerful telescopes and a long observation time. Useful for stars evolution and formation.

Metal lines These lines become stronger at the temperature decreases and dominates the spectra of F,G and K stars.

Molecular lines Form in cool stars (M, L. T-types) The stellar flux is significantly reduced in the regions of the spectrum where we have molecular transmission. We have different kinds of molecular transitions: electron transitions (optical and UV), vibrational transitions (IR), rotational transitions (radio waves).

2.4 Age from the MS knee

This age derivation method is based on near infrared photometry, so we need to observe the CMD in the infrared. The MS knee is a feature of the CMD caused by the collision-induced absorption of molecular hydrogen and other molecules. In the MS knee we have a dramatic change in direction of the main sequence.

If we take stellar populations with different ages the vertical distance between the MS knee and the MS turn off is indicative of the age of the stellar population. Increasing the age of the stellar population the position of the MS knee is fixed but the position of the turn of changes, becoming bluer and brighter as the population gets younger. As the population gets older the vertical distance decreases.

The advantages of this method are:

- not dependent on cluster distance
- not dependent on cluster extinction
- not dependent on photometric calibration (same error both on the knee and on the turn off)
- large number of stars and we don't have to deal with variable stars

It also have some disadvantages:

- MS knee stars have often faint luminosity
- if we go at lower temperatures we have also the effect of molecules
- the luminosity of the MS knee is strongly affected by oxygen abundance so stellar populations with the same age but different oxygen abundance may exhibit MS knees with different luminosity

2.5 Stellar parameters from spectroscopy

Most relevant stellar parameters

Effective temperature Temperature of the black body which is characterized by the same luminosity and radius of the real star:

$$L = 4\pi R2\sigma T_{eff}^4$$

Surface gravity Usually is expressed in cgs units and as $\log_{10}$:

$$g = GM/R^2$$

Metallicity Fraction of metals in the star (elements that are not H or He)

$$Z = \frac{\text{mass (elements heavier than He)}}{\text{total mass (unit volume)}}$$

$$[Fe/H] = \log [N(Fe)/N(H)]_\star - \log [N(Fe)/N(H)]_\odot$$

$$[\alpha/Fe] = \log [N(\alpha)/N(Fe)]_\star - \log [N(\alpha)/N(Fe)]_\odot$$

It is easier to work with the normalized spectrum so we take the observed spectrum and we derive the continuum and then we normalize the spectrum with respect to the continuum in such a way that the continuum as a flux equal to 1. Then we can proceed to quantify the information form the lines.

2.5.1 Measuring abundances: equivalent width

The equivalent width tells us how much flux is absorbed by a specific line. It is defined as the width of a rectangle whose height is equal to the the height of the continuum and whose area is equal to the integrated area of the line. It does not depend on the shape of the line neither on the rotation of the star. To determine the abundance of an element using the equivalent width we need to use the **curve of growth** which describes the equivalent width of a line as a function of the column density of the material from which the spectral line is observed.

We can derive different regimes of the curve of growth with different slopes:

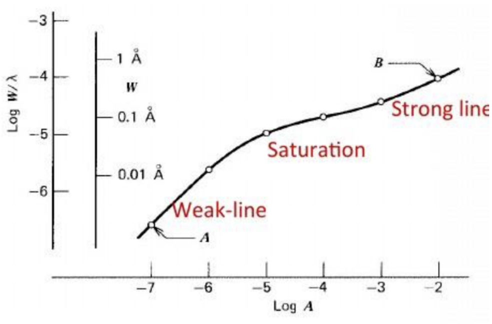


Figure 2.1: Curve of growth

- **Weak line** - linear part of the plot where the EW is proportional to the abundance of the element. In this region of the plot we can derive precise abundance determination. In these lines the doppler broadening dominates.
- **Saturation** - we have a plateau. In this region is not convenient to derive chemical abundances. The doppler core reaches its maximum and and increase/decrease of the abundance of an element corresponds to negligible variation of the EW. In this regime we have $W \propto \sqrt{\log A}$
- **Strong line** - wings dominate. The optical depth of the wings become dominant and we have $W \propto \sqrt{A}$. Strong lines are not appropriate to derive the chemical composition of a star but they are quite useful to derive the gravity of the star.

2.5.2 Temperature determination

We need to use as many lines of the same element as possible. In cold stars we mostly use iron lines. The effective temperature of a star is not dependent on the excitation potential of the individual lines. We need to iteratively determine it till when we find the right ET. In this case our program will output a straight horizontal line.

2.5.3 log(g) determination

Ionization balance In cold stars we use the ionization balance to derive the gravity. We take lines corresponding to the same element in different ionization stages. For example Fe I and Fe II. If we increase gravity the EW of the Fe I line remains almost the same while the one of the Fe II line decreases. As a consequence log(g) can be derived by enforcing Fe I and Fe II to have the same abundance.

Strong lines In hot stars we can use strong lines to derive log(g) since their wings are sensitive to the change in gravity. So we take the observed spectra and then we compare its strong lines with models of spectra characterized by different gravity. Remember that the strength of lines depends also on effective temperature and on the abundance so in order to make comparison between models and observations we need to fix the chemical abundance.

In real life we have two main problems: spectra can be affected by blends and crowding. This means that lines are close and blended together, increasing the difficult to derive the EW. Crowding and blends are associated to the resolution of the spectrograph. Sometimes increasing the resolution of the spectrograph is not enough to untangle different lines so we have to use other techniques like **spectral synthesis**: basically we compare the observed spectra with grids od simulated spectra with different chemical composition and abundances.

2.5.4 Alternative approach: multi-band photometry

When we take images at the telescope these images are in gray scale. To observe the sky with colors we have to take three different images in three different bands (RGB channels). The color we derive in this way is indicative of the ET and the chemical composition. From observations red stars are cold and blue stars are hot.
But how can we derive precise determination of ET and gravity using photometry? We need to connect colors to ET using appropriate color-temperature relations. Basically we derive these relations for a bunch of well studied stars and for different intervals of metallicity. When plotting it we find a well defined trend so knowing the color of a star we can derive its ET.
A major problem of this technique is the reddening (but we should not care about distance after correcting for reddening, it is a relative measurement).

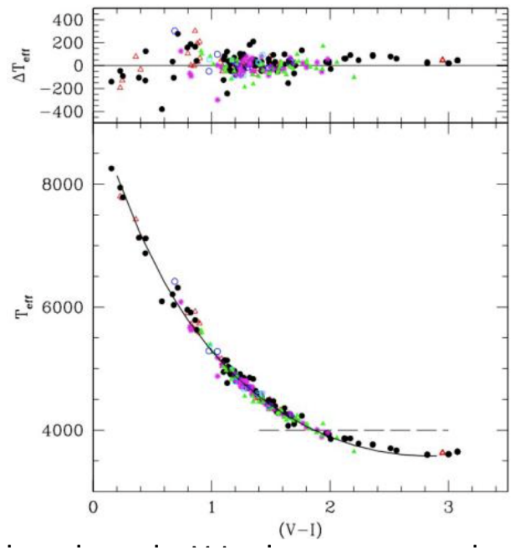


Figure 2.2: Color - effective temperature relation

2.5.5 Opacity

The opacity κ indicates the ability of stellar matter to absorb radiation (energy transport equation). We need to consider all the microscopic processes that can absorb photons at each frequency ν. Different processes: bound-bound, bound-free, free-free absorption and electron scatter. The opacity depends on level population, ionization balance and electron density so $\kappa_\nu = \kappa_\nu(\rho, T, X_i)$.

2.5.6 Balmer Jump

For wavelength lower than 365 nm photoionization from the level n=2 can occur. As a consequence we have an increase in opacity and a drop in stellar flux at wavelength shorter than the threshold. This is a good indicator of the effective temperature in hot stars and in colder stars is a good indicator also of the gravity. In fact if in cold stars we fix the temperature and we change the gravity the Balmer jump significantly change.

2.6 Stroemgren photometry

To maximize the sensitivity to certain parameters we can design some filter combinations. One of these filter systems is called Stroemgren and is characterized by 4 main broad/middle band filters, which are u, v, b and y. The u filter is in the UV range and the v filter is comparable with the blue standard filter. By combining the b-y filter we have an indicator of the continuum slope of the black body so it is efficient in constraining the effective temperature of the star. A color index c=(u-v)-(v-b), sensitive to the Balmer discontinuity is a good indicator of the gravity of the star. Another color index m=(v-b)-(b-y) is sensitive to the blanketing so it is a good indicator of the metallicity of the stars. Then there are two narrow filters called beta filters and centered on the Hβ line.

The Stroemgren photometry is a combination of colors and pseudocolors that are sensitive to the chemical composition, reddening, gravity and effective temperature of the stars.

2.7 Infrared flux method (IFM)

This is an efficient to infer the stellar parameters by using photometry alone. It is based on the comparison between the flux in the IR with the bolometric flux of the star. The filters are in the infrared and optical region. This method allows to derive the effective temperature and the stellar angular diameter (which is unknown for the majority of stars) with big accuracy.

2.8 Lithium Cosmological Problem

The lithium problem is one of the challenges for the Big Bang nucleosynthesis confirmation. First of all we have to remember that the CMB shows us that the universe is not uniform but there is an anisotropy and that from comparison between the model and the observed anisotropy we are able to contrain the ratio between baryons and photons when radiation and matter decouple with each other. From the CMB we know that the lithium abundance is $[\mathrm{A(Li)}] = 2.72 \pm 0.06$.
The production of lithium depends on the temperature and density of the primordial universe. We know that Li is a very fragile element and burns at a quite low temperature ($T = 2 \cdot 10^6$ K). Lithium can be produced in the interstellar medium by collision with cosmic rays or during the evolution of intermediate mass stars. If we are able to find pristine material in the universe, the amount of lithium in that material should correspond to the Li abundance of the Big Bang nucleosynthesis. So if we have metal poor stars formed just after the BB, their Li abundance should reflect the same abundance of Li of the BB. Using the CMD from an old, metal poor GC with a small distance modulus.
We set two limits in the CMD, one at the RGB bump and one at the middle of the SGB: in these point we have some events of mixing some material from the interior (no lithium content) of the star to the surface (pristine lithium content). Lithium is destroyed when is injected to the center of the star and it is destroyed so the final Li content is lower than the pristine one. But if we take stars that are not evolved, the Li amount is constant and is not affected by mixing processes and so it is indicative of the primordial Li content.

Comparing the results with the expectations we see that the Li is constant in the main sequence, then we have a drop due to the red clump. We observe that the level of Li is 2.3 but the one we expect is around 2.7 so we have a disagreement. This is called the **cosmological lithium problem**.

How can we explain this? There are several options:

- BB nucleosynthesis is not entirely correct;
- Li abundance determination are not correct due to some errors in the determination of the effective temperature or other parameters;
- Errors in the understanding of stellar atmosphere and line formation of Li;
- Particle physics involved in the BBNS;

- Unknown effects in stellar evolution responsible for a tiny Li depletion. It is possible that there is a region in the star where there is a mixing of interior and surface material that causes depletion on Li. This mixing could be due to rotation, diffusion or other exotic things like gravitational waves.

Chapter 3

Differential reddening

Looking at two different CMDs, we can see that sometimes they are more narrow and other times they are broadened. Why does this happen?

If we look at the map of reddening of the galaxy we can see that there are some clouds and that the reddening changes based on where we look. It is also not uniform along the spectrum because it varies with the wavelength, it is small in teh red part of the spectrum and grows moving to higher frequencies.
The extinction law is indicative of the direction of the reddening of the CMD and changes as a function of $1/\lambda$. The reddening law we deal with is described by the ratio $A_V/E(B-V)$ which is equal to R_V which is equal to 3.1. In the UV the ratio is high, in the IR is smaller.
But if we go in different directions we have different reddening laws so different values of R_V. This effect is called **differential reddening**. It causes a big impact in the determination of the distance scale and the properties of stellar parameters at large distances.

3.1 Schlegel reddening map

This is the first work to derive maps of the clouds in the sky, using a combination of satellites to create an high resolution map of the reddening across the whole sky. The maps use the far IR intensity ratio at 100/200-micron to measure the dust temperature. For this reason, they trace the dust column density in this wavelength. This is a determination of dust column density and reddening that is of course reddening dependent. The model works well when dealing with a single dust temperature across a given lien of sight. If we have a messy region, with lots of clouds we have a lot of uncertainties. So this map is good in regions far from the galactic plane but doesn't work well for complex clouds. We need to research for an empirical approach based on the features of the CMD.

3.2 The RGB bump and the Red Clump

When looking at the CMD we can see that the density of stars decreases going toward brighter luminosity, which is connected to stellar evolution. There are some overdensities of stars, which are very detectable if we create a luminosity function of RGB stars. These are the RGB bump and the Red Clump.

3.2.1 The RGB bump

The RGB bump is a clump of stars along the RGB. When a star goes through the RGB, it is characterized by the presence of the hydrogen burning shell moving from the cental region of the star to the outer part. During this transition the hydrogen burning shell approaches the chemical discontinuity left behind by the first dredge up (drop of the Li abundance) and we have a drop in the stellar luminosity. Once the shell went trough the discontinuity the stellar luminosity increases in a monotonic way. So we have the situation seen in Fig. 3.1: the same star crosses the same point in the luminosity temperature plane three times causing an over density of points in the CMD.

3.2.2 The Red Clump

The red clump is a clustering of stars in a different phase with respect to the RGB bump. It is a clustering of stars that burn hydrogen in the core, they're kind oh horizontal branch stars but belong to a different population, younger and more metal rich. RC stars are slightly hotter than RGB stars with the same luminosity. The red clump characterize young and metal rich populations.

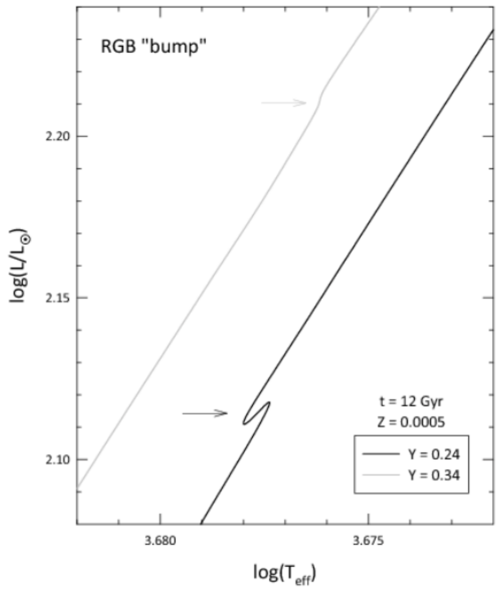


Figure 3.1: Explanation of the RGB bump.

3.2.3 The Galactic Bulge CMD

We can use these features to infer properties of the clouds between us and the galactic bulge. The GB is massive ($\log(M/M_\odot) \sim 10$) and old around 10 Gyr. It is heavily obscured by interstellar clouds and is huge so we can only observe it small pieces at a time and it is difficult to reconstruct it in its whole.
The bulge is composed of complex multiple populations with different ages and metallicities, its CMD is very different from the ones we are used to. The GB formed at relatively high redshift.

How can we investigate the different stellar populations in the bulge? First we have to get rid of spurious sources and to correct for differential reddening by combining HST information with GB surveys. But how can we get rid of the differential reddening along the direction of the GB? In this direction we have a region of chaos with multiple clouds so we need empirical tools to measure the differential reddening and to correct for it.
We can use the **red clump**. The GB is made of stellar populations that are not so old and are metal rich so we can easily spot the red clump. If we take a small region of the sky the amount of differential reddening is small so we can distinguish the main features of the CMD. From surveys we see that the CMD of the bulge exhibit the RGB bump, but because of differential reddening we can't distinguish between the red clump and the RGB bump.

The color and magnitude of the red clump can change dramatically in CMD of stars in different fields of view. The relative color and magnitudes of the red clump are indicative of the direction of differential reddening. Stars that are far away from the galactic plane are brighter while stars that are closer to the galactic plane are fainter. In the end we have CMDs that are shifted along a given direction and this direction is the one of the reddening line.
Moreover, by comparing the relative position of the red clumps in terms of color and magnitude we can derive the amount of reddening in each region of the sky.
By doing that with different CMDs of different regions of the sky we can make a map of the differential reddening in the direction of the bulge. This reddening determinations are empirical. By comparing the maps produced in this way with the Schlegel map we see that there are discrepancies up to 0.3 mag. However we can use these maps due to the fact that their resolution is not enough and we may have CMDs with broadened features for which we cannot say if the broaden is due to differential reddening or if it is intrinsic.

Chapter 4

Exotic objects in the CMD

4.1 Luminosity profiles

Luminosity profiles are mathematical laws used to describe the luminosity of a cluster (ideal cluster, made only of stars), and are basically the luminosity against the radius of the cluster.
It is described in terms of:

- **core radius** r_c: distance at which the surface luminosity drops by a factor 2, half of the central value;
- **half-light (mass) radius** r_h: radius within half of the luminosity (therefore the mass) of the cluster is included;
- **tidal radius** r_t: radius where the gravitational influence of the galaxy around the cluster is larger than the influence of the cluster itself, so the radius where the cluster ends.

One of these luminosity profiles is the **King profile** given by:

$$f = k \left\{ \frac{1}{[1 + (r/r_c)^2]^{\frac{1}{2}}} - \frac{1}{[1 + (r_t/r_c)^2]^{\frac{1}{2}}} \right\}^2 \tag{4.1}$$

The main parameter that describes the King profile for a star cluster is the **concentration** of the model $c = \log_{10}(r_t/r_c)$.
Some luminosity profiles exhibit a deviation from the predicted law, especially at small radius. Why?

4.1.1 Core collapse

In 15% of the clusters the luminosity continues to increase all the way to the core region, as shown in Fig. 4.1, so we have a discrepancy between the observations and the King profile. This tells us that stars are collapsing towards the center, so we have **core collapse** which is a **catastrophic dynamical process** consisting in runaway contraction of the core of a star cluster. All stars should collapse in one single event but this does not happen. This is due to the presence of binary stars that are mostly saved from collapsing because we have binary-binary and binary-single collisions that delay or prevent the cluster from collapsing and reaching infinity central densities. We can try to predict this using n-bodies simulations.
However the overdensity if stars in the core of the cluster can be associated even to other phenomena and not only to core collapse.

4.1.2 Intermediate mass black holes

Core collapse is not the only responsible for the central luminosity increase. Another explanation could be the presence of an intermediate black hole in the center of the cluster.
However the presence or lack of a black hole in a GC is still controversial because it is very difficult to measure the distribution of light or velocity at different radial distances.
Within a cluster there could also be some clustering of other dark objects, like neutron stars. From the point of view of stellar dynamics, a **cluster of neutron stars** can also behave like a black hole in first approximation.

4.2 Binaries in star clusters

We can measure the number of binaries in a cluster only for a limited range of luminosity due to the presence of photometric and observational errors. We can divide the CMD in two different regions, one containing all the stars

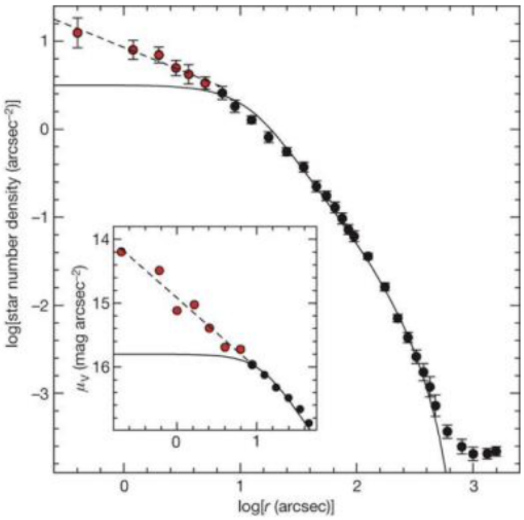


Figure 4.1: Evidences of core collapse in a stellar cluster.

(region A) and one containing the binaries with a mass ratio bigger than 0.5 (region B), then we count the stars in these regions and we derive the binaries fraction. So we can derive the fraction of binaries using the following relation:

$$f_{bin}^{q>0.5} = \frac{N^B_{\text{real}} - N^B_{\text{field}}}{N^A_{\text{real}} - N^A_{\text{field}}} - \frac{N^B_{\text{art}}}{N^A_{\text{art}}} \tag{4.2}$$

where "field" means field stars, "art" means photometric blends. Doing so for many cluster we find that the fraction of binaries anti-correlates with the mass of the cluster, meaning that massive clusters are characterized by a small fraction of binaries while low mass clusters have a large fraction of binaries. Moreover the fraction of binaries does not correlate with the age or the rate of collision of the cluster. In a star cluster we have a precise relation between mass and luminosity, due to the fact that there is no significant amount of dark matter in GCs.
We have other relations:

- the fraction of binaries is maximum at the center and decreases of a factor 2 at a distance of 1 core radius;
- the fraction of binaries does not depend on the mass ratio, the number of equal mass binaries is the same as different mass ones;
- the fraction of binaries does not depend on the mass of the primary star

Due to these consequences we can say that knowing the binary fraction we can get the absolute magnitude as a consequence of the mass of the stellar system. This is not true for all GCs: in fact if the binary fraction is too small this relation is no more satisfied for what concern the total mass. But the absolute magnitude is always a proxy of the visible mass and the missing amount of mass is dark matter mass. So the binary fraction can be used as a method to infer the presence of dark matter in these objects.

4.3 Blue Stragglers

Blue stragglers (BS) are main sequence stars in a stellar population that are brighter and bluer than stars at the main sequence turn off. They are among the brighter stars in the UV band. These kind of stars are not expected in a CMD. If fitting the CMD by an isochrone we can see that BS seem consistent with stars that are younger than the bulk of stars, as we can see in Fig. 4.2. So what are BS? We have some different explanations:

1. They are **field stars** that have been included into the cluster due to gravitational interaction. This hypothesis is easily excluded if we use spectroscopy because we can see that they have the same metallicity as the stars in the cluster.
2. There was a **recent star formation** within the cluster.
3. **Differential reddening** but this hypothesis can be excluded because the other sequences in the diagram are not broadened, we have a spread of point only in the area of the BS.

There are two main proposal to explain the formation of BS:

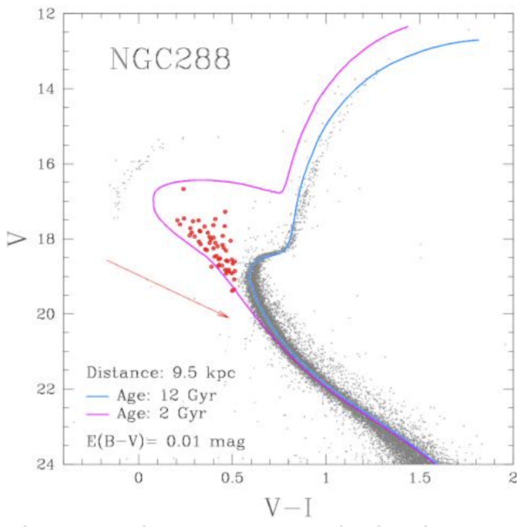


Figure 4.2: In red are highlighted the blue stragglers. We can see the two different isochrones used to fit the stellar population and the BS.

- **Collision -** It can happen in a very dense environment: stars interact in a gravitational sense, then collide and generate a star characterized by a mass bigger than the mass of the two components. The star would still be burning hydrogen coming from the two stellar components so it looks like it is younger but actually it's not. This phenomena occurs in the main sequence so before the star evolves.
- **Mass transfer or coalescence of primordial binaries -** We have two binaries orbiting around the same gravitational center. At some point the primary star starts transferring material to the secondary star through the inner Lagrangian point, filling the Roche lobe and the material is stripped off the primary star. The secondary star become more massive and prolongs its life because it gets more hydrogen to burn. The BS has then a life longer than a normal star with the same mass, which explain the position of the star in the upper main sequence. In this scenario we would expect a naked star, the primary star from which the material was stripped off, which can be detected using spectroscopy (we won't see the usual absorption lines).

If BS were formed through collision we would expect a different chemical composition of the stars because during the collision there is little to no mixing between the inner core and the external part of the star so we expect to find the same chemical composition as the initial chemical composition of the two stars. So basically the BS should have the same chemical composition of the other stars of the cluster.

In the case of mass transfer we have that the mass that has been transferred comes from the inner region of the donor star where **partial CNO processing** has occurred. We know that during the CNO cycle the nitrogen abundance increases while the carbon and oxygen abundance decreases. In terms of metallicity, the total content of C+N+O remains constant because we have the transformation of one element into the other due to nuclear reactions so the single abundance of each individual element will be different, but the overall content remains the same.
So in case of mass transfer we expect a content of C and O much lower than the standard content of stars. This has some consequences on the absorption lines associated to the elements.
Looking at the chemical composition of BS they found out that most of them have the same chemical composition as normal stars, but some of them are **strongly depleted in C and O** with respect to the dominant population. This is considered an evidence that in the atmosphere of BS there are CNO burning products that come from the internal region of a companion star. This is a confirmation that the mass transfer scenario is correct. But remember that only some BS are characterized by this feature.

The mass transfer scenario works only if we are in a binary system, so we expect some kind of correlation between BS and binaries. We find out that also BS anti-correlates with the mass of the cluster, and so with its absolute magnitude. On the other side if BS formed from collisions, we expect to find a lot of BS or a correlation between BS and collision rate. However there is no correlation between them.
So we can conclude that we have some evidence for mass transfer but only in some BS and no evidence for collision.

Let's see now if there is any kind of correlation between BS and binaries. By plotting the fraction of the binaries and the one of BS we find a beautiful correlation. Moreover the fact that the fraction of binaries depends on the mass of the cluster but not on its age nor on the collision rate is consistent with the mass transfer scenario.
There are several works that are in contradiction with what we have just said. For example, looking at the cluster

M30, we can see that there is a bimodality in color distribution of BS, which indicates that we have both populations of BS (collision and mass transfer).

BS to derive the dynamical age BS can be used to infer the dynamical age of stellar systems. This can be done by measuring the radial distribution of BS. In stellar clusters we have the phenomenon of radial segregation, which means that massive objects go into the center of GCs if the stellar system has evolved for some time.
To measure the dynamical age we measure the fraction of BS at different radius. In some cluster the distribution of BS against the radius is flat: those clusters are **dynamically flat** (Family I). Then we have a different family where we have a maximum value at the center, then a drop, and then a second peak: these clusters have an **intermediate dynamical age** (Family II). The last family (Family III) is composed by **dynamically old** clusters and we don't have the presence of the secondary peak.
The segregation of BS is connected with the **gravitational interaction** of objects. Because of that the stars in the cluster lose kinetic energy and momentum and the dynamical friction drives objects more massive than the average towards the center with an efficiency that decreases with increasing radius.

4.4 Cataclysmic Variables

The cataclysmic variables (CVs) are exotic binaries formed by a **white dwarf and a cool secondary star**, a low mass star. The secondary star transfer mass to the WD, forming an accretion disk in which the material loses gravitational energy and emits at high energy, like in the X-rays. For this reasion we find them by observing the core of a GC in X-ray: in this way we see only few objects that emit at a very high energy.
CVs can be found in the region between the MS and the WD. This binary system is distinguishable from the MS and the WDCS only if the light from the two stellar components is comparable with each other. If not, the binary system will be too close to one of the branches.
To be sure to be looking at a CV we use the properties of its spectrum: in fact the spectrum of a CV have some lines in emission and not only in absorption like the other stars. We can analyze all the stars in the field using photometry and a filter centered in the Hα region: if we have an excess of luminosity of a star, that star is a CV. These stars are more centrally concentrated than MS turn off stars. In fact for a fixed radius we have a larger fraction of CVs than of MSTO stars.
We can divide them into bright and fain but they are equally segregated. In bright CVs the secondary star has a mass of about 0.9 $M_\odot$ while the WD's mass is around 0.5 $M_\odot$. In faint CVs the secondary star has a mass lower than 0.2 $M_\odot$ and the WD's mass is similar.

There are also other kinds of exotic binaries:

- Millisecond pulsars (MSPs);
- MS binaries with flare outbursts;
- Low mass X-ray binaries that contain a neutron star.

4.5 X-ray variables

X-ray variables are close binary systems which are sources of X-ray emission. Basically they consists in an expanding star that is filling its Roche Lobe and transferring material that spins up the compact companion (neutrons star or BH). The outburst in the X-ray indicate that heavy mass accretion of the neutron star is taking place. We have three main classes of XRV:

- **Canonical binary MSPs**: host a He WD companion with mass of 1-0.5 $M_\odot$
- **Red back**: the companion is a MS star with mass 1-0.5 $M_\odot$
- **Black widow**: the companion is an almost exhausted MS star or a brown dwarf smaller than 0.1 $M_\odot$

4.5.1 Hunting low-mass X-ray binaries (LMXBs)

How do we detect those X-ray objects? Let's make an example.
In 2015 an increase in emission in direction of **Terzan 5** was detected in the Swift/BAT hard x-ray monitor, located at 6.8 arcsec form the optical counterpart of the neutron star EXO 1745-248.
Terzan 5 has been classified as a GC but it has some strange features so it could be a peculiar GC with extreme properties in terms of multiple stellar populations. It is a stellar system with a very high stellar density, an ideal place

where to study stellar interaction and evolution.
After having detect the increase in emission, HST was immediately pointed in that direction to produce the CMD of the GC and to detect the optical counterpart. When observing in the optical regime and outside the outburst phase, we observe the companion, not the x-ray source. The CMD of T5 is shown in Fig. 4.3, where is highlighted the position of the star in the quiescent state and during the outburst. We can see that the CMD is quite a mess, extremely dense and affected by reddening. When the star was quiet it was in the sub giant branch so it was a star that exhausted the hydrogen core and started burning H in the outer part. This star is leaving the MS, expanding and becoming a red giant branch star. This means that the expanding star is our donor and is transferring mass to a neutron star, which is increasing its acceleration and starts emitting in the x-ray.

EXO 1745-248 provides a link to the evolutionary chain connecting LMXBs to MSPs: the x-rau emission indicates heavy mass accretion on the neutron star and this process is responsible for the acceleration of the MSP.

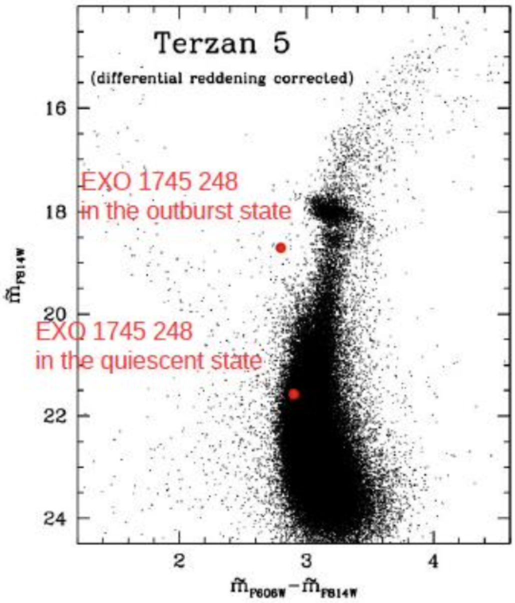


Figure 4.3: CMD of Terzan 5. The red dots indicates the position of the source in the quiescent and in the outburst state.

Intial Mass Function

The initial mass function is the mass of the stellar population when it formed. It is difficult to derive since we observe the present day mass function, but if we deal with young stellar populations we can some mass functions that are close to the IMF. The most famous representation of the IMF is the one proposed by Kroupa, shown in Fig. 4.4. He suggested a segmented IMF, where the stars are divided into three intervals depending on their mass. For massive stars ($M > 0.5\,M_\odot$) there is a correlation with the Salpeter IMF. The value $0.08\,M_\odot$ is the threshold for the hydrogen burning so below this value we talk about brown dwarfs and not about stars. The slope of the IMF changes with respect to the mass of the stars: it increases as the mass decreases.

If we look at old stellar populations in terms of dynamical age, we see that the IMF changed because of the kinematics of stars. When dealing with young stellar populations we have poor statistics so we have fluctuations in the IMF. Moreover we have to pay attention to differentiate between binaries and single stars. All these problems may affect the determination of the IMF.

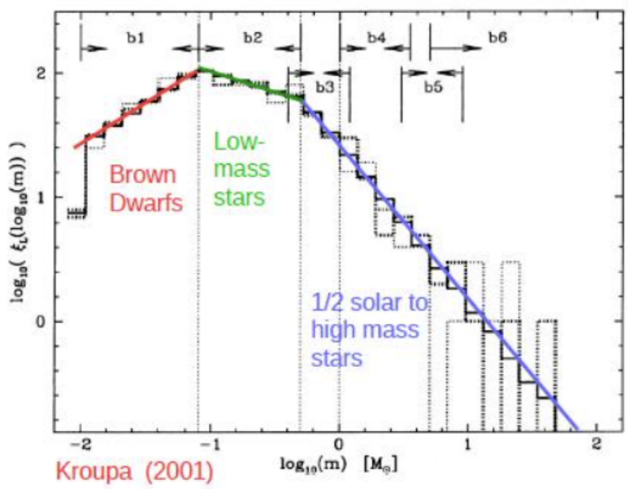


Figure 4.4: Kroupa initial mass function

Chapter 5

Black Holes and First Stars

5.1 Hunting black holes

5.1.1 Massive black holes

Super massive black holes are present in the center of massive galaxies. One of the main techniques to derive the properties of BH is to take spectra of the gas present in the central region of the galaxy. The motion of the gas in this region is strongly affected by the presence of the BH. Through spectroscopy we can derive the rotation curve and we can also see that, comparing this spectrum with the one taken in the outer part of the galaxy, the first one is blueshifted and redshifted. This is an evidence for the fact that there is keplerian rotation around the center of the galaxy and the high velocity speed is demonstrating that we are dealing with a super massive object.

There is a relation, the **M-sigma relation**, that relates the velocity dispersion of the galactic bulge to the mass of the super massive black hole.
Looking at the center of the Milky Way there is **Sagittarius A**, a compact radio source at the center of our galaxy. In the central light year of our galaxy is located a dense star cluster and we can see that there are stars orbiting around something that is not visible to us. By studying the orbit of one star is possible to derive the mass of the BH which is $(4.10 \pm 0.60) \cdot 10^6\,\mathrm{M}_\odot$, so it is a massive black hole. We have massive BH in almost every massive galaxy.

5.1.2 Intermediate mass black holes

Obviously if we go to galaxies with lower masses, the mass of the central BH decreases. So if we want to study intermediate mass BH we have to analyze galaxies and stellar systems that have masses of the order of $10^6\,\mathrm{M}_\odot$.
We can use other techniques to infer the presence of a BH. For example we can use a method based on the **luminosity** and the **velocity profile**. We expect these stellar systems to be well described very well by some models, like the King profile.

Let's make an example. We analyze the GC Omega Centauri, which has a mass of $10^6\,\mathrm{M}_\odot$, but that once was more massive, so massive that was able to retain in its potential well the gas that was ejected by supernova winds which collapsed in the center of the GC along with some pristine material. By studying its luminosity profile we can see a deviation from the King's profile (Fig. 5.1) due to the strong effect of the BH. The observations are consistent with the profile of the **luminous component** plus a **dark component** in the inner region.
By making other models and plots, considering the velocity dispersion of the stars against the radius, was found that the observations are consistent with the presence of a BH with a mass of $4 \cdot 10^5\,\mathrm{M}_\odot$, which can be considered an **intermediate mass black hole**. However, if we analyze the proper motions of the stars around the BH, we have no evidence of such a massive BH. The mass of the black hole should be 4 times smaller that the one just found, around $12000\,\mathrm{M}_\odot$.

5.1.3 Stellar mass black holes

To search for stellar mass black holes we have to analyze compact objects because we expect them to form in high density environment. We can study globular clusters. To study them we will use a technique based on **radial velocity** but that is based on **integral field spectroscopy**. To do so we can use **MUSE@VLT**, which couples the potential of an imaging device and of a spectrograph, making photometry and spectroscopy at the same time.

Gravitational waves can be produced by the merging of two stMBH. The first detection of gravitational waves

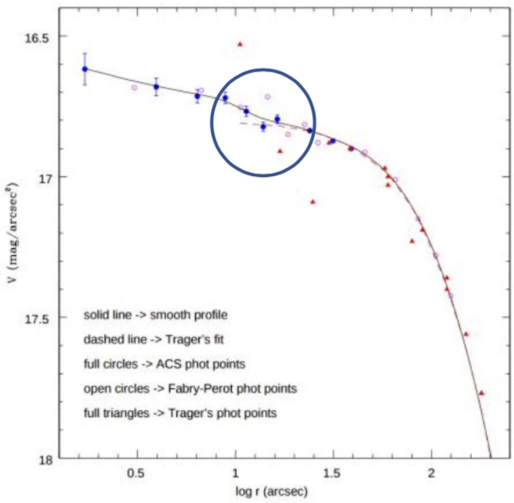


Figure 5.1: Luminosity profile of Omega Centauri. In the circle we can see a deviation from King's profile.

was produced by the coalescence of two massive black holes. This suggest that dense star clusters represent a preferred environment for the merging of such black hole binaries.
Looking at **NGC 3201** with MUSE was detected a star with radial velocity variations of the order of 100 km/s: this star is a main sequence turn off star with a mass of $0.8\,M_\odot$, neither radio nor x-ray source is known at the target's star position. The radial velocities measurements exhibit a period of 167 days and radial velocity variations of about 150 km/s.
By comparing the observations with different models of BH characterized by different mass and orbital properties we see that the companion is consistent with a detached **stellar-mass black hole** with a minimum mass of $4.36\pm0.41\,M_\odot$.

5.2 Hunting the first stars

The first stars that formed in the universe are population III stars, a metal-free population that lit up the universe about 100-200 Myr after the Big Bang.

During the BBNS were produced only **hydrogen**, **helium** and **lithium**, so the first stars should be composed only of these elements, we would observe only H and He in the spectrum of these stars.
There are several ways to detect population III stars:

- Observing at **high redshift** (cosmological approach);
- Using the **21 cm line** (cosmological approach). It is used to get information about the matter of the universe at very high redshift. In the early universe the temperature of the electron spin was the same as the cosmic microwave background (CIB), but when the first stars formed the electron spin temperature changed and connected with the temperature of the gas. In this situation the gas was absorbing more 21 cm photons than emitting. After a while the first black holes formed and started heating the gas by emitting high-energy radiation, so the gas became too hot to emit or absorb 21 cm photons. So basically we would expect a drop of the temperature of the 21 cm emission line when the first stars born, followed by a period where the temperature was almost constant, followed again by an increase when the first BH formed.
- Observing nearby present-day stars in very high detail and use them to infer the properties of the first stars (galactic archaeology).

Bowman and its team took observations, using a radio wave antenna, of the early universe producing a map of the CMB of the entire sky. The observed spectrum is dominated by **synchrotron emission** coming from the Milky Way which has to be subtracted using some models. After this subtraction the residuals are at a level of 0.1-0.2 K, while the starting signal was at about 5000 to 1000 K (becomes cooler ah higher frequencies). This result need to be improved using 21 cm line models. The final result is the third plot in Fig. 5.2: we observe that the temperature is constant around 0 for a given range of low frequency, then we have a drop in temperature, the signal remain constant for a while and then increases again.
We can then convert from frequency to redshift (Fig. 5.3). At around z=20, when the universe was 180 Myr we have a drop in temperature, which was due to the formation of the first stars. The temperature then shows a plateau followed

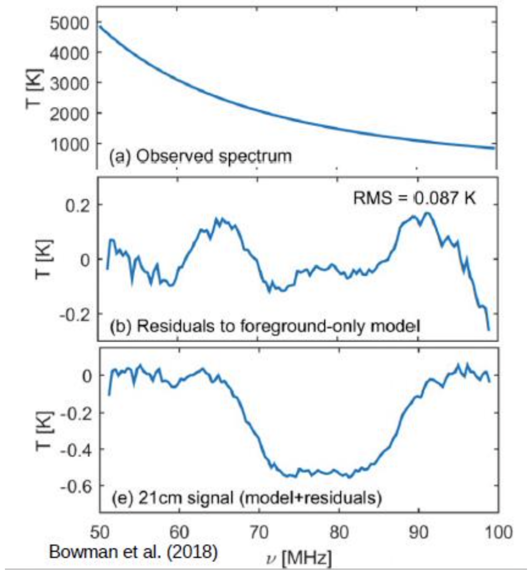


Figure 5.2: CMB emission, before and after the correction for synchrotron and 21 cm line.

by an increment, consistent in time with the formation of the first black holes. The width of the plot, which indicates the period between the birth of the first stars and the formation of the first BH, is consistent with the theories. The main discrepancy between theory and observations regards the depth of the plot: this is twice as deep as expected. The gas was colder than predicted? A possibility to explain this issue is that the temperature of the CMB is wrong but this is not possible because this temperature is well known and proven (T=2725 K).
The only thing in the early universe colder than the CMB was **dark matter**. Maybe the hydrogen lost some of its heat to dark matter? This should not be possible because dark matter and regular matter interacts only through gravity. We should break this paradigm and account for another type of interaction so to reproduce the depth of the 21 cm line.

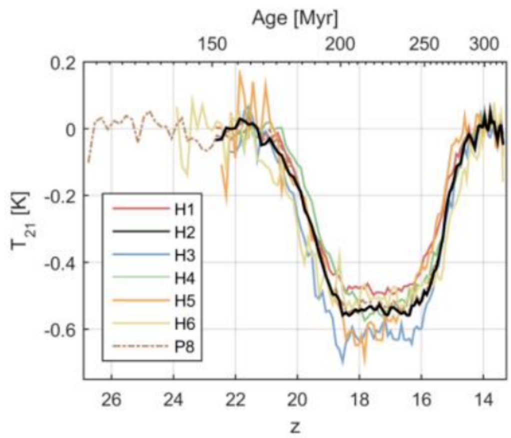


Figure 5.3: Temperature of the 21 cm line as function of the redshift.

5.2.1 Population III stars

Population III stars are metal-free stars, their chemical composition should reflect the composition of the matter after the BBNS (H, He and Li, no metals). **Are these kind of stars still present in today universe?**

A possibility is that pop III stars were characterized by a top-heavy mass function. For example, if these stars were characterized by a Kroupa IMF, the massive part of the stellar population should not be visible nowadays because massive stars would have already evolved/disappeared and we would observe only stars with masses $< 0.8\,M_\odot$. So, if we assume a different IMF for pop III stars, is possible that most of them would have had masses bigger than $100\,M_\odot$. In this case very massive stars have a short lifetime and we are not able to see these stars in today universe.

In any case pop III stars were very luminous so, even if we can't see them now, they should have left a trace in the CIB and its intensity is not affected by the chosen IMF. We can then try to infer the properties of pop III stars from CMB and CIB. The main questions are:

1. **Where** are pop III stars? Are they still **alive**?
2. What are the **properties** of pop III stars?
3. To what extent pop III stars contributed to the **re-ionization** of the universe?

5.2.2 The Milky Way

The MW is composed by a galactic disk, in particular by a thin disk plus a vertically extended disk and even a more extended metal-weak thick disk. The thin disk is composed of young and metal-rich pop I stars ([Fe/H]~-0.2), the thick one has stars with [Fe/H]~-0.6 and the metal-weak thick disk hosts stars even more metal-poor $-1.0 <$[Fe/H]< -2.5. Then there is the stellar halo that has a spheroidal distribution that envelops the disk and the bulge and teaches out to $\sim 150\,\mathrm{kpc}$ and contains old pop II stars.

5.2.3 Population III stars in the Milky Way

We can start searching for pop III stars looking at the halo of the MW, which contains the most metal-poor stars of our galaxy and is not affected by a significant amount of galactic extinction. Since we were not able to find any pop III star we can start looking at second-generation stars that were born from pop III supernova ejecta mixed with pristine gas. So we look for second-generation low-mass metal-poor stars that are observable at present day.

Since to do so we need high resolution spectra that are really expensive in terms of time and money, we follow this approach:

1. select candidate metal poor stars from **photometry** (Sky Mapper, uses different filter set to identify stars with different metallicities);
2. observe candidates with **low resolution spectroscopy** using intermediate class telescopes;
3. follow up best candidates at **high resolution** using large telescopes.

The Keller star This is the most metal poor star, it has almost **no iron lines** and a metallicity of [Fe/H]~ -7.5. We know that iron is a proxy of metallicity so if we have no iron do we have a pop III star? This is not true because in this star we have evidence of Ca, Mg and high C content. So this star could be born from the material ejected from a pop III star. We need to look at the chemical composition of the star to understand the properties of the **progenitor** of this star.
For sure its progenitor can't a SN with mass lower than $10\,\mathrm{M}_\odot$ because SN with mass lower than this threshold release a large amount of iron. Neither is a very massive SN (mass higher than $70\,\mathrm{M}_\odot$) because these SN produce a low amount of C and an high amount of nitrogen. In conclusion the progenitor of Keller star should be a **low energy intermediate mass supernova** ($50\,\mathrm{M}_\odot$). But why this kind of supernova does not produce iron?
This is due to the fact that in massive stars we have the formation of a **central BH** while it is collapsing so the star releases into the ISM only the lighter elements from the outer layers but elements in the internal part of the star are trapped inside the BH. That's why this kind of SN matches perfectly the chemical composition of the Keller star.

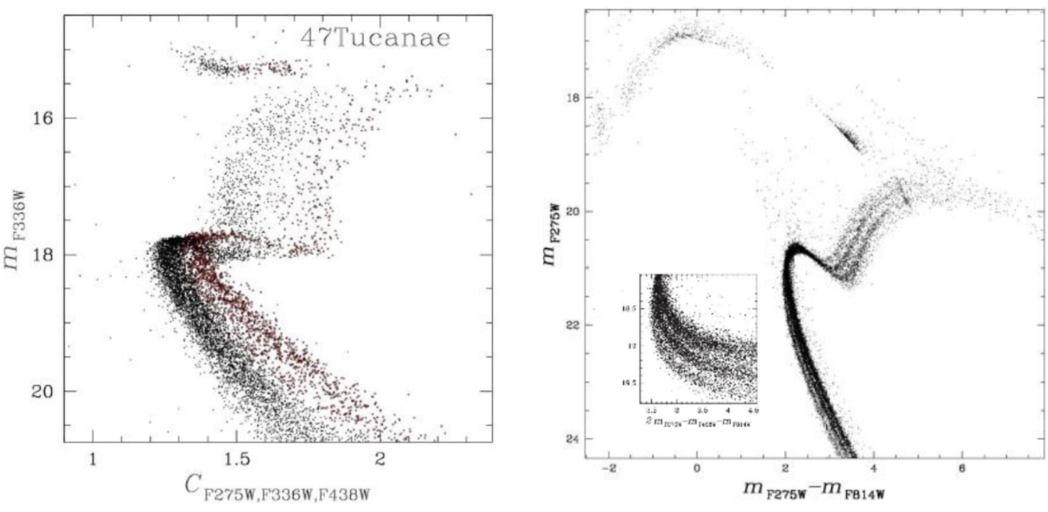
The Norlander star Another study was done on a star with metallicity of [Fe/H]~ -6.2 which contains a small amount of iron, a pop II star. It was found that the star formed from the ejecta of a low energy supernova of a pop III star of about $10\,\mathrm{M}_\odot$.

The David Yong star This is a star with [Fe/H]~ -3.5, so not so metal-poor, but with an unusually high amount of some elements like zinc, uranium and europium, which are indicative of the **rapid r-process** elements, usually produced when we have **neutron star mergers**. However neutron star mergers alone cannot reproduce the observed element abundance patterns so the Yong star indicates the existence of other sources for forging if r-process elements. The high amount of zinc is the signature of a **hypernova** (i.e. a very energetic supernova). The element abundance pattern is well matched with the yields of a **zero-metallicity 25 $\mathrm{M}_\odot$ magneto-rotational hypernova** so the Yong star formed out of a chemical soup that contained the remnants of this type of hypernova mixed with some pristine material.
Hypernovae are associated with γ-ray bursts in the nearby universe and the fact that we observe the signature of hypernovae in the early universe are an indicator of the fact that hypernovae were also present at very high redshift (earliest epochs of star formation) and that pop III stars can evolve as hypernovae.

Chapter 6

Multiple populations in young and old star clusters

In old CMDs we can see that we have very narrow sequences with isochrones that fits very well the points, so GCs were considered prototypes of simple stellar populations. However now the situation dramatically changed due to space based facilities and computational facilities that improved the quality of photometry. On today's best CMDs we can see **multiple sequences** visible at all evolutionary phases.
We can build super CMDs (Fig. 6.1) using different combinations of magnitude. For example we can define color combinations in the UV-optical blue range that are sensitive to stellar populations with different content of nitrogen or helium (wide color baseline that is sensitive to differences in temperature among stars with similar luminosity). In the CMD sensitive to the helium abundance we have three discrete sequences along the different evolutionary phases. We can see that CMDs sensitive to different chemical abundances are quite different so how can we maximize the information from these diagrams?



(a) (b)

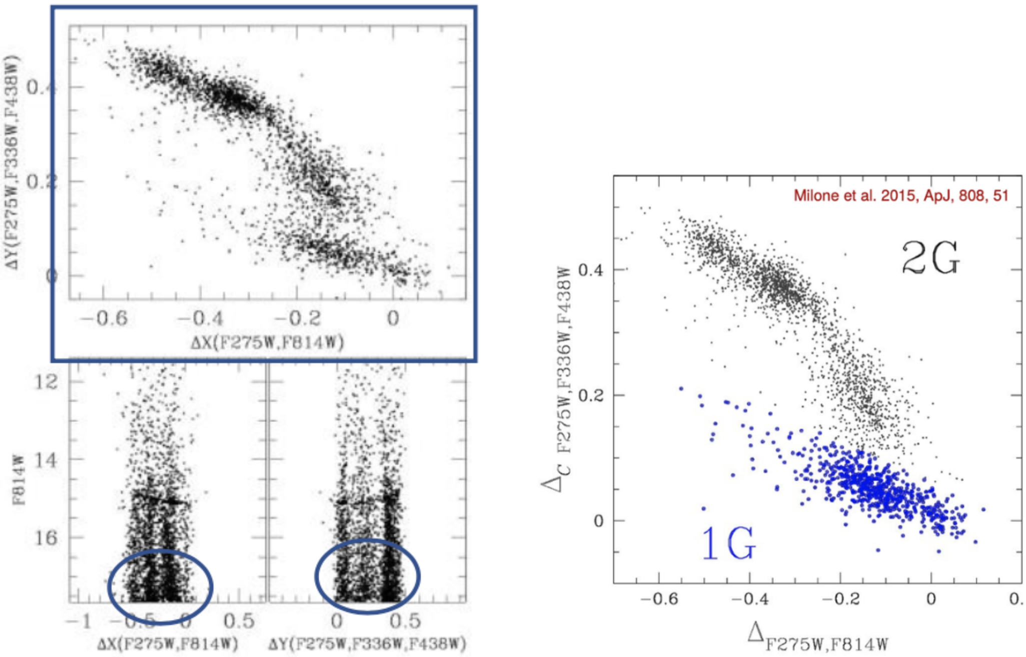
Figure 6.1: In Fig. 6.1a we have a super CMD sensitive to the nitrogen abundance while in Fig. 6.1b we have a super CMD sensitive to the helium abundance.

6.1 The Chromosome Map

We define a new photometric diagram that combines together the information from the super CMDs, called **Chromosome Map (CM) of GC**. The position of each star in the CM is indicative of its chemical composition. How do we build this diagram?

The CM can be derived only for stars in the same evolutionary phase so we have to build CMs for RGB, MS or AGB stars separately. To build it we have to choose one evolutionary phase, for example the RGB, and we have to derive the **boundaries** of it in both super CMDs (nitrogen and helium sensitive). Then we **verticalize** the CMD

in such a way that the boundaries correspond to two vertical lines. In this way we get an interval of color along the x-axis called **pseudo color**. Once we have derived the pseudo color for both the super CMDs we can plot one RGB sequence against the other forming the chromosome map (Fig. 6.2a).
The position of each point in the map is indicative of the chemical composition of the stars in particular of its nitrogen or helium content. We notice that stars are not distributed in a single blob, as we expect in the case of SSP, but they are distributed into **multiple different blobs** (Fig. 6.2b).



(a) **(b)**

Figure 6.2: Fig. 6.2a: how to build a chromosome map. This map regards the RGB: the verticalized CMD on the left is the super CMD sensitive to the nitrogen while the one on the right is the one sensitive to the helium. Fig. 6.2b: difference between 1G and 2G stars.

We have 1G (first generation) stars, close to the origin of the reference frame that have a chemical composition identical to the chemical composition of the stars in the galactic halo, then we have 2G (second generation) stars that have abundances of He, N, Mg that are only observed in GCs. The 1G extension is consistent with either helium or metallicity variation while the 2G extension is due to nitrogen variations (Fig. 6.3). We point out that the variation in He within 1G is not associated to stellar nucleosynthesis since there is no sense, for standard chemical evolution, to have stars with the same amount of nitrogen but different amount of helium. We have to address this variation to some strange, exotic phenomena.

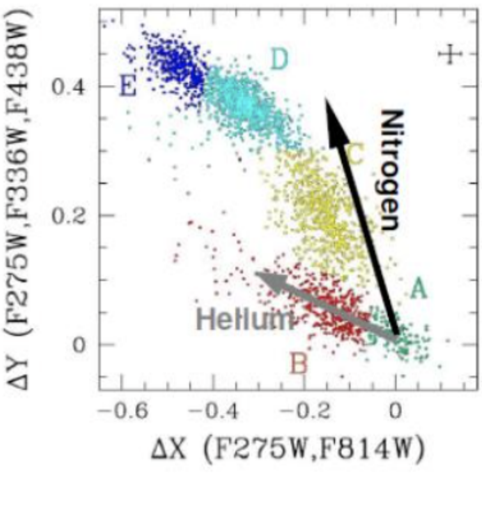


Figure 6.3: Nitrogen and helium abundance variations along the chromosome map.

6.2 10 properties of multiple populations

1. 1G-2G discreteness We do not see continuous stellar distribution, we see two different discrete blobs that can be easily separated one from the other.

2. Ubiquity All globular clusters have multiple populations. Simple stellar population GCs are quite rare.

3. Variety The distribution of stars in the CM, the extension of the map, the number of blobs in the 1G and 2G changes from one cluster to another, there are no identical clusters.

4. Type I and type II GCs There are two main classes of GCs, as we can see in Fig. 6.4. **Type I GCs** are the 'normal' ones, where the stars all belong to the black sequence and we can distinguish 1G and 2G stars. This type is associated to the majority of GCs, the 82%.
Type II GCs, also called **anomalous GCs** are characterized by a second anomalous sequence of stars, here highlighted in red, associated to stellar system more complex than a standard GC. Those anomalous GCs are considered as a new class of stellar systems, like an intermediate object between normal GCs and dwarf galaxies. They could also be dwarf galaxy remnants, a results of their dynamical evolution.

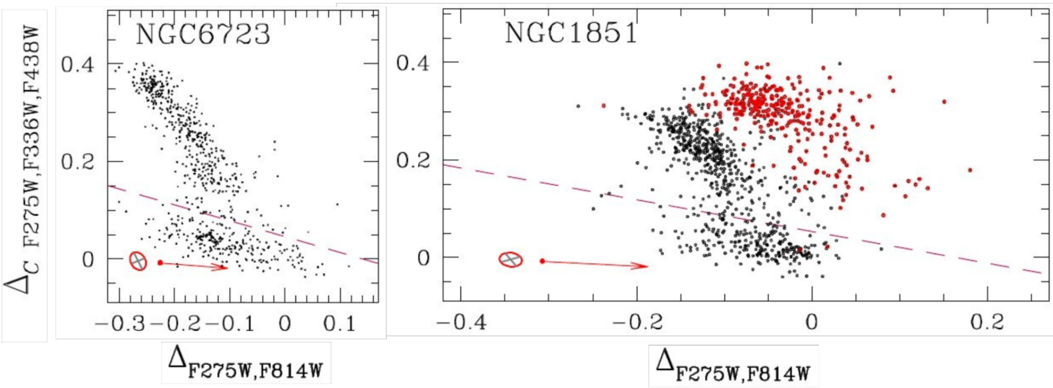


Figure 6.4: Chromosome maps of type I (on the left) and type II (on the right) globular clusters.

5. Dependence on cluster mass Properties of MSP like the maximum amount of chemical variation and the fraction of second generation stars depend on the mass. In particular in massive clusters the 2G stars are the majority of cluster stars while in small mass cluster we almost have half 1G and half 2G stars. So the fraction of 1G stars anticorrelates with the mass of the cluster. Moreover the maximum nitrogen variation correlates with the cluster mass

6. Maximum helium enhancement of Y$\sim$0.43

7. Dependence on galactocentric distance and on host galaxy Clusters with large perigalactic radius host larger fractions of 1G stars than small-perigalactic radius ones. Moreover the presence of MSP depends on the environment. In fact if we take a collection of chromosome maps of cluster of the Small and Large Magellanic Cloud we can see that there are some clusters that are consistent with simple stellar populations, more than in the MW. In addition Magellanic-cloud clusters host larger fractions of 1G stars than milky way globular clusters.
The difference disappears when considering the initial masses so its like GCs lost most of their first generation. We made a simulation assuming that the fraction of 1G stars is related to the initial mass of the GC and we assumed that a GC preferentially loses 1G stars and in this way we were able to match the observations.
This gives us another question: is there a mass threshold? We are able to say that only GCs with initial masses bigger than $10^5\ \mathrm{M}_{\odot}$ may host multiple populations.

Formation scenarios

There are different scenarios for what concerns the formation of multiple populations. The two main scenarios are:

1. **Multiple generations stars -** Different stellar populations corresponds to different generations of stars. The proto-GC had a complex star formation history with multiple bursts of star formation. If this scenario is correct (GC much more massive at star formation), then GCs have lost most of their first generation stars into the galactic halo/galaxy. They can be building blocks of galaxies and could have provided a major contribution of the reionization.

2. **Single generation -** The GC had a simple stellar formation and the multiple blobs in the CM are the product of some exotic phenomenon. Multiple sequences are the result of accretion of some material that is chemically polluted by stars from the same generation. In this scenario GCs did not provide significant contribution to the assembly of the galaxy and to the reionization of the universe. In this way we would have some explanations of exotic objects such as huge massive stars that should be responsible for the pollution of material from which second generation stars formed.

8. No dependence on stellar mass Most of the information on multiple populations is provided by massive stars ($\sim 0.6 - 0.8\,M_\odot$), multiple populations of low mass stars are almost unexplored. Since is not possible to get faint precise UV photometry for faint stars we can use the water molecule to unveil multiple populations of very low mass stars. In the plot in Fig. 6.5 we see the spectra of two stars that are identical in terms of stellar structure and parameters but have different chemical composition. Oxygen is one of the elements that is distinctive between 1G and 2G stars: 1G stars are characterized by high oxygen, they have the same amount of oxygen as normal stars in the galactic halo, while 2G stars are depleted in oxygen. As a consequence the absorption due to water molecules is less pronounced in 2G stars.
If we use isochrones with different amounts of oxygen we can describe even the most exotic CMDs. This indicates that MSP observed at high and low masses are characterized by the same content/difference of oxygen. This is not consistent with the scenario where 2G stars formed through a Bondi accretion of material polluted by massive stars. In case of accretion we expect that the separation of the sequences in the CMD gets smaller and smaller when the star become fainter and fainter because the amount of oxygen that is accreted depends on the mass so it is small in case of low mass stars.
We can conclude that the properties of MSP along massive stars are the same as the properties od stellar population along low mass stars.

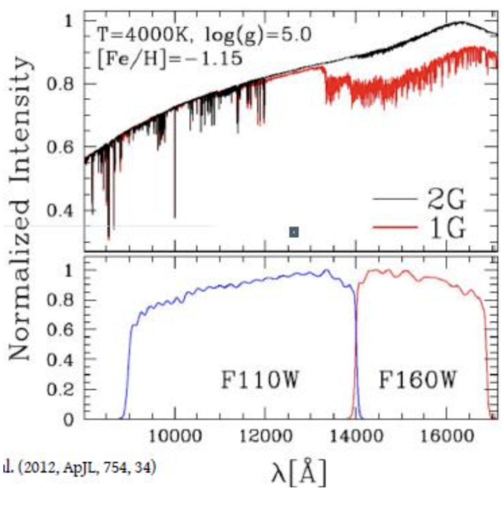


Figure 6.5: Spectrum of 1G and 2G stars.

9. More centrally concentrated 2G stars We expect that most clusters population are mixed in the center. However we observe 2G stars are often more centrally-concentrated than the 1G.

10. 2G stars exhibit anisotropic motions 2G stars show stronger anisotropies and smaller tangential velocity dispersion than the 1G, consistent with the idea that 2G stars formed in the innermost cluster region in a very dense environment.

6.3 Formation scenarios for multiple populations

We know that we can infer the age of star clusters by using the magnitude difference between the main sequence turn-off and the main sequence knee. However there is an huge problem: the luminosity of the MS knee is strongly affected by oxygen abundance, stellar populations with the same age but different oxygen abundances exhibit MS knee with different luminosity.

We have various formation scenarios:

- multigeneration scenarios (each blob in the chromosome map is a different generation of stars in a temporal way)
- alternative scenarios

6.3.1 Asymptotic Giant Branch scenario

The first generation of stars forms with a full IMF (like Kroupa or Salpeter), then massive stars evolve faster than low mass ones. When these massive stars reach the end of their life, they explode as SNe and **eject the material** at super-high speed. As a consequence of these **high velocity wind**, clean all the intra-cluster medium, emptying all the cluster and leaving a **cluster made only of stars**, with no residual gas. After 20-30 Myr stars do not explode as SNe anymore and the most massive stars evolve as AGB stars.
The proto-GC is now formed only by 1G stars and no gas. AGB stars starts ejecting some material that is not pristine but processed within the interior of the star. This material is characterized by a **strange chemical composition** in the sense that the matter that composes the AGB winds is enhanced in H, He, depleted carbon, oxygen because the material has been processed by nuclear reactions in the interior of the star. This ejected material is not expelled outside the cluster, is collected in the cluster center where now we have a mix of pristine gas and polluted gas by AGB stars. The material collapse in the cluster center and we have a **new episode of star formation**, which corresponds to the formation of 2G stars in the cluster center.
When we have the explosion of SNe of 2G stars we have an **increase in energy** that makes the cluster expand. In the external part of the cluster we have 1G stars that can be lost from the cluster. AGB stars are the **polluters** proposed to explain the chemical composition of 2G stars. However AGB model is not able to explain the high He abundance.

6.3.2 Fast-Rotating Massive Stars

In this scenario the polluters are fast rotating massive stars (with masses $\sim 25 - 250\,\mathrm{M}_\odot$) that lose mass through a slow mechanical equatorial winds and produce material rich in H-burning products. This material form a disc around the star. The formation of 2G stars occur due to gravitational instability in these discs, which are fed both by the FRMS ejecta and pristine gas.

The mass-budget problem

Both these scenario have a main problem: second-generation stars are born out from the material polluted by first-generation massive stars. But the present day second generation comprehend the majority of cluster stars.
If we try to compute the mass of the progenitor of a CG is $\sim 2 \cdot 10^8\,\mathrm{M}_\odot$. Multiplying this estimate by 200 (number of cluster in the galaxy), we find that the total amount of gas needed to form all galactic GCs is $\sim 4{\cdot}10^{10}\,\mathrm{M}_\odot$ with $\sim 4{\cdot}10^9\,\mathrm{M}_\odot$ dissolved 1G stars. Such a mass is comparable with the mass of the Galactic halo.

The consequences of this are:

- the progenitors of GCs were as massive as dwarf galaxies and lost most of their 1G stars;
- they could provide a significant contribution to the mass of the galactic halo;
- they could provide a significant contribution to the reionziation of the universe.

6.3.3 Single generation scenario

In this scenario we have no multiple generations but multiple populations: all stars formed at the same time but some stars changed their chemical composition halfway due to some exotic phenomenon.
In this scenario we assume that in the early universe there were **super massive stars** ($10^4\,M_\odot$). GCs form in converging gas flows and accumulated low angular momentum gas, which accretes onto protostars. This leads to an **adiabatic contraction** of the cluster and an increase of the stellar collision rate.
A super massive star can form via runaway collisions if the cluster reaches sufficiently high density before two body relaxation halts the contraction. This condition is met only if the number of stars is $> 10^6\,M_\odot$ and the gas accretion rate is $> 10^5\,M_\odot/\mathrm{Myr}$, reminiscent of GC formation in high gas-density environments, such as the early universe. This scenario is able to explain the presence of multiple populations in both old and young clusters.

So we have that SMS wind mixes with inflowing pristine gas, the protostar accrete diluted material processed by the SMS (also some pristine material). In principle the life of such a massive star is short but since there is a continuous amount of material that falls into the big star, there is a process of **rejuvenation** of the massive star. Because of this rejuvenation the amount of material ejected by the SMS can be 10 times higher than its mass. This would provide a solution to the mass budget problem. The material ejected by the SMS is enriched in helium and in C, N and O. According to this scenario we expect a correlation between the amount of processed material and cluster mass: the bigger the cluster, the larger amount of processed material. These theories are confirmed by the observations. Remember that in this scenario we do not have multiple generations of stars, the stars are all coeval and we have the accretion of polluted material of 1G stars. The super massive stars could have formed by accretion of the material in the pre main sequence phase, and their accretion is proportial to the mass of the stars (Bondi accretion). The main challenge of this scenario is the fact that we observe multiple populations along very low mass stars. We do not have observational evidences of super massive stars: the most massive stars ever found are $100\,M_\odot$ and are located in the cluster 136a.

6.4 Type I and type II GCs

M4 Type I GC, composed of a single sequence, simple cluster. The distribution in the sodium-oxygen plane is not the same of normal stars in the galaxy, we can distinguish 1G and 2G stars. Stars with different chemical composition distribute on different sequences both in the CMD, as we cna see in Fig. 6.6.

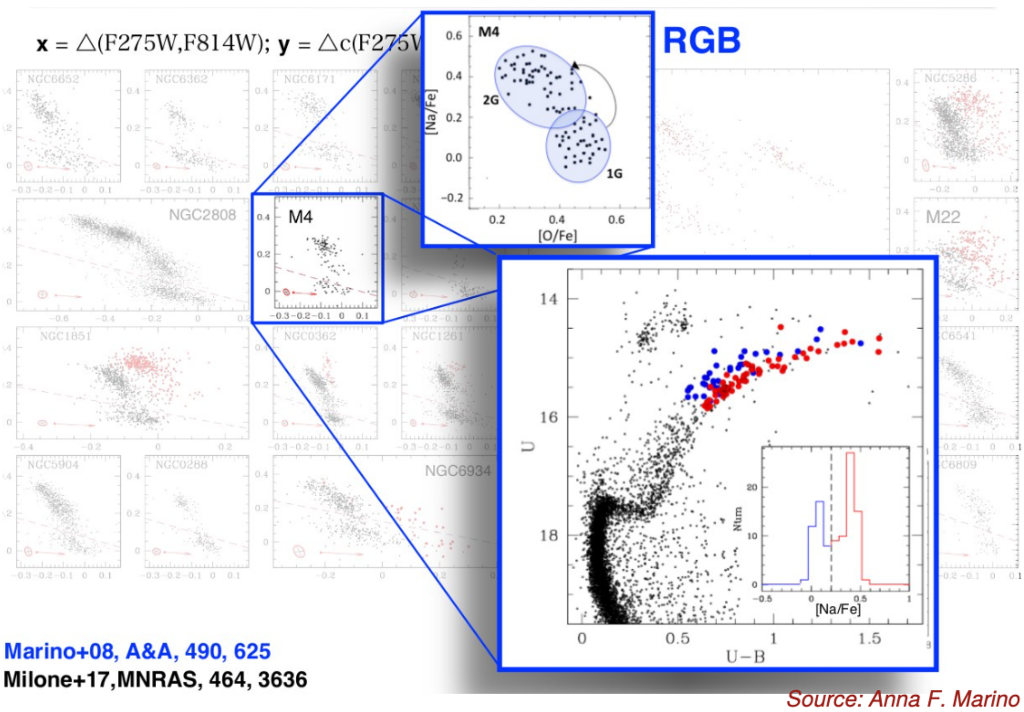


Figure 6.6: Chromosome map and CMD of the cluster M4.

NGC2808 Type I GC, composed of a single sequence but this time is a complex cluster (Fig. 6.7). We have at least 7 populations, with multiple populations within 1G stars and multiple discrete populations in 2G. We can see that stars are not chemically homogeneous, there are stars depleted in O ([Fe/O]=-1).

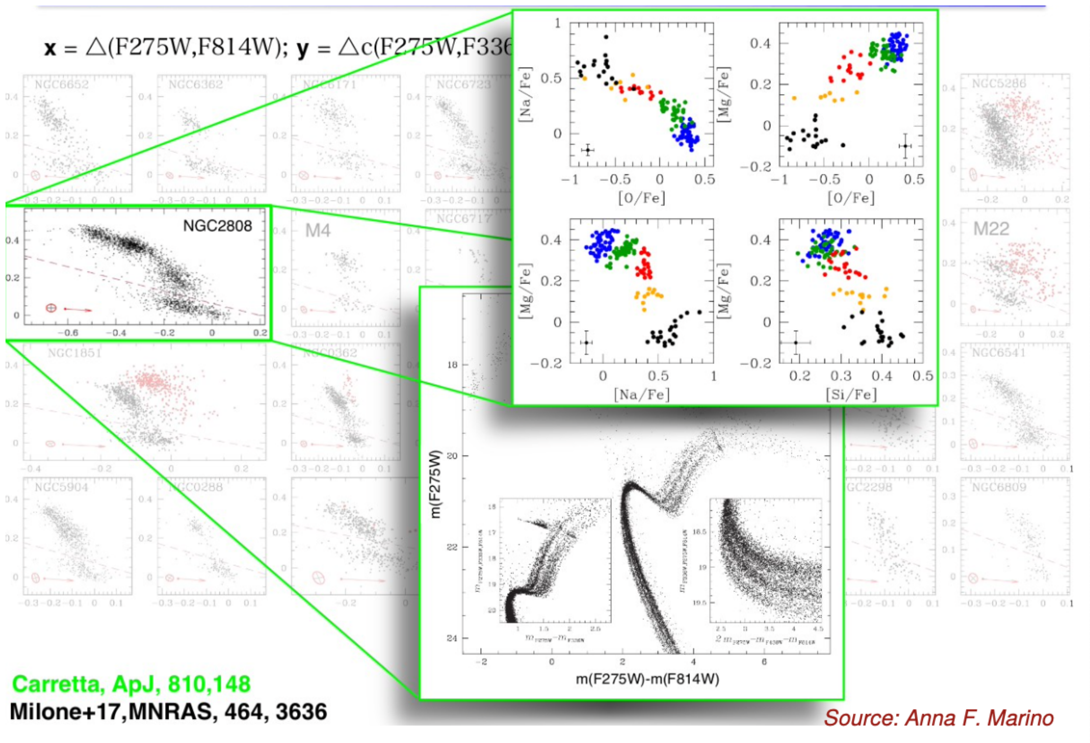


Figure 6.7: Chromosome map and CMD of the cluster NGC2808.

Type II GCs

Let's remember some features of type II cluster: they are characterized by a split in the SGB visible in UV CMDs and optical ones associated to the stellar structure itself, and they are not homogeneous in terms of iron. So we have: variations in metallicity, in s-process elements, in C+N+O abundance (something more than hydrogen burning). Metallicity variations are characteristic of galaxies and not of GCs, so it is possible that those objects are bridges between galaxies and GCs.

M54 Looking at the CM of M54 we see that we have the red component (Fig. 6.8). This is important because M54 is located in the nucleus of a Sagittarius dwarf galaxy, in a process of being disrupted by the MW. So we can conclude that we can have GCs as nucleus of dwarf galaxies that can disappear. Can we link this conclusion to the missing satellite problem?
We know that simulations based on the ΛCDM model predict that dark matter clusters hierarchically and we expect to have a small number of massive satellites of dark matter and a large number of smaller ones (large number of dwarf galaxies). But we do not see such a large number of dwarf satellite galaxies. If we have that T2 GCs are naked nuclei of galaxies, maybe they make a significant contribution to the missing satellites problem. In conclusion it is vey tempting to speculate that anomalous GCs similarly to M54 are the remnants of dwarf galaxies cannibalized by the MW.

NGC1851 This is a type 2 GC characterized by the split of the SGB, it has a strange chemical composition and is surrounded by a visible halo outside the tidal radius containing the 0.1% fo the dynamical mass of NGC1851. This halo is not extreme, it is a spherical halo. How is it possible to have a small mass of stars linked to the stellar cluster with such a low density? A speculation is the fact that this halo must be composed mostly of dark matter.
With spectroscopy and radial velocities analysis we see that stars outside the tidal radius have an high redial velocity and so they are linked to the cluster. Concerning the chemical composition we see that the normal and anomalous population have different distributions in terms of iron. Inside the cluster we have two groups of stars with different chemical composition in terms of s-process elements but in the halo we have only stars with pristine chemical composition, so s-poor stars.
We can conclude that NGC1851 is the nucleus of a dwarf galaxy disrupted by tidal interactions with the MW, and the halo represent the relic of the dwarf galaxy where the cluster was embedded. The fact that there is dark matter is confirmed by radial velocity studies.

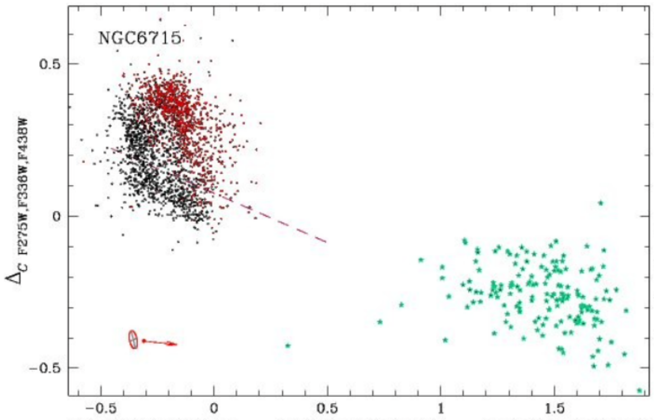


Figure 6.8: Chromosome map of the Type 2 cluster.

6.5 The extended main sequence turn off phenomenon

All GCs in the Milky Way formed at high redshift so we can study them to see how are old GCs. However we want even to study GCs that are forming now. To do so we can study two nearby satellites: the **Large** and the **Small Magellanic Cloud**. In these systems there are a lot of star clusters that have a wide range of ages (mostly GCs that are forming now and intermediate age GCs). These two satellites are perfect to study multipopulations phenomena due to their proximity to us.

We taught that young star clusters were prototypes of single isochrones. However is not like this: in fact if we look at the CMD of NGC1866 in Fig. **??** we can see that there is a **split in the main sequence** and we have a phenomenon called **extended main sequence turn off** (eMSTO). The latter is a common feature of $\sim 1-2\,\text{Gyr}$ star clusters in both Magellanic Clouds. The split does not concerns the whole MS, we have a merge at some point. This is due to the fact that in that point the star changes the energy transmission mechanism (from radiative to convective) but the precise physics has not been completely understood.
The case of NGC1866 is not isolated, successive observations led to the fact that this happens quite often.

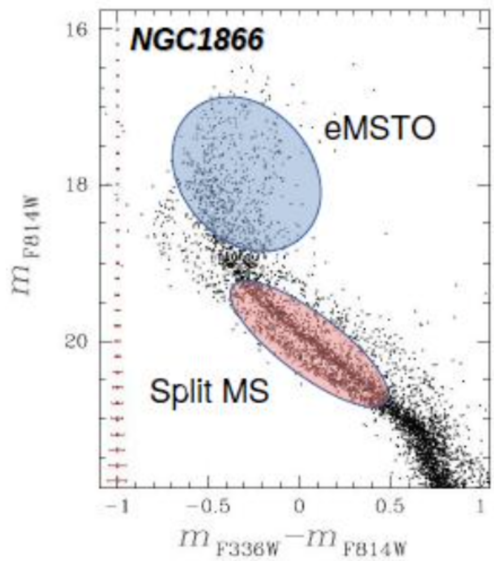


Figure 6.9: CMD of the cluster NGC1866, located in the LMC. It hosts a split MS and an extended MSTO (eMSTO).

What causes the double MS and the eMSTO? To find the cause we can compare the system with different isochrones, varying the main stellar parameters. We try different combinations:

- **different helium abundance**: no, there is no splitting in the MS;
- **different metallicy**: no, reproduce the MS splitting in the central part but there is no convergence;

- **different age**: cannot reproduce the totality of the splitting but reproduces quite well the eMSTO, it's ok but not enough;
- **different rotation rates**: coeval stars but different populations have different rotation rate, mimic the eMSTO very well.

Rotation rates When a star rotates becomes elongates so observing it edge on or face on makes an huge difference. As a consequence the temperature, the color and the luminosity will change depending on the inclination of the line of sight, which is totally random. With this in mind we can conclude that there will be some scatter in the CMD due to these different inclinations. This implies that we can't just compare isochrones and CMDs directly, we have to deproject first and then compare.

We can call the two different part of the MS '**red MS**' (upper-right part of the CMD) and '**blue MS**' (lower-left part). When comparing the spectra of the blue and the red MS, observing their spectral lines, we see that the ones of the blue MS are **narrow** and well defined while the ones of the red MS are very **broadened**. This is a signature of **rotation**.
After some observations we can conclude that the double MS is consistent with two stellar populations with different rotation rates and the eMSTO is consistent with prolonged star formation (different ages). There are evidences that even coeval stellar populations with different rotation rates can mimic the eMSTO. However we can't completely rule out age differences.

Through the comparison of Globular Clusters in the MW with young and intermediate age MCs clusters and MW Open Clusters we can identify some similarities, as shown in Fig. 6.10.

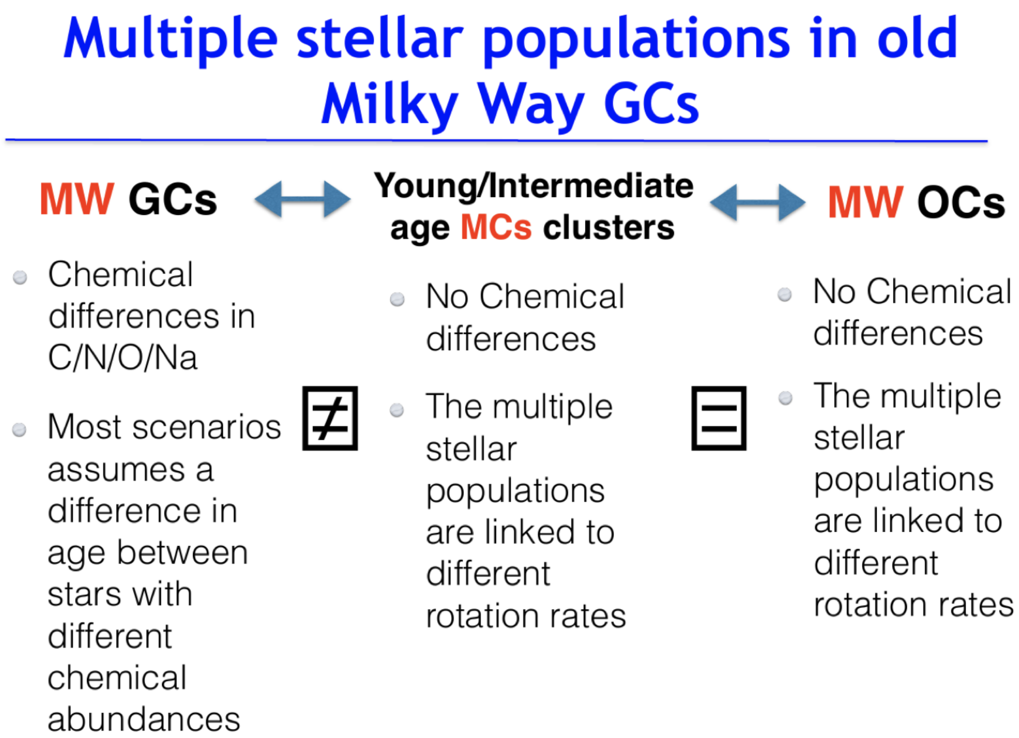


Figure 6.10

Chapter 7

The Milky Way

7.1 The Bulge

The Galactic Bulge (GB) is a massive and old component of the MW, its CMD is difficult to derive due to the extension of the bulge itself. Moreover is heavily contaminated by disk stars which significantly affects the MS turnoff (but it can be statistically decontaminated).
Most of the stars in the GB are old stars, only a tiny fraction ($\sim 5\%$, upper limit, there are blue stragglers) is consistent with a young stellar population. The age of the bulge is determined by comparing the CMD with isochrones. The bulk of bulge stars belong yo old population with ages of $\sim 10 - 12\,\text{Gyr}$, which suggests a rapid star-formation, confirmed by the high $[\alpha/\text{Fe}]$ ratio.
This CMD suffer for **low-scale differential reddening** and we have to deal with many galactic components in the same field of view (**field contamination**). To solve the second problem we can observe in the Baade window (relatively low interstellar dust) to identify bulge, disk and clusters stars using proper motions. Then cluster members are used to derive an high resolution reddening map in the Baade window that is then used to correct the (proper motion selected) CMD of bulge stars for differential reddening. We see that the CMD is characterized by broadened MSs and RGB.

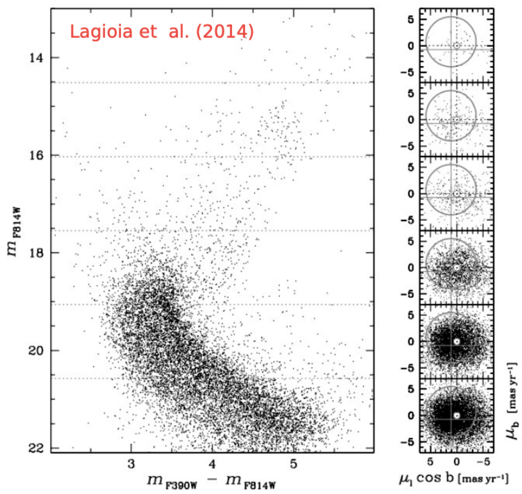
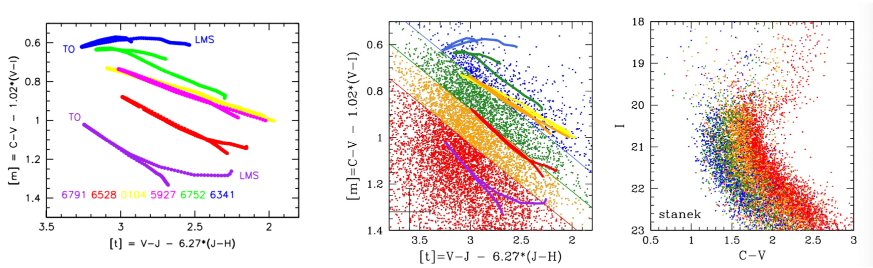


Figure 7.1: Color-magnitude diagram of the galactic bulge

There is no sharp distinction between the bulge and the disk, when we talk about disk we refer to the inner $\sim 3\,\text{kpc}$ of our galaxy.

7.1.1 The age of the GB

An alternative method to infer ages for bulge stars is based of the so called five-band HST photometry in five fields. We build pseudo color-color diagrams made with a combination of colors and magnitudes that ensures that the total amount of reddening is almost zero. In this diagram populations will look like single isochrones, metal poor populations will follow the blue line, metal rich ones will follow the violet one.



(a) **(b)**

Figure 7.2: Isochrones (a) and isochrones applied to a pseudo CMD (b) to infer the age and the metallicity of GB stars.

We can use the diagram to differentiate between different populations. Then the CMD can be recomposed: in blue metal poor stars, in red metal rich ones.

Comparing this photometry-derived age with the age derived from spectroscopy of microlensed dwarf galaxies and stars we see a huge discrepancy. Ages inferred with spectroscopy are lower than the ones inferred with photometry. Is this an evidence for a two component bulge?

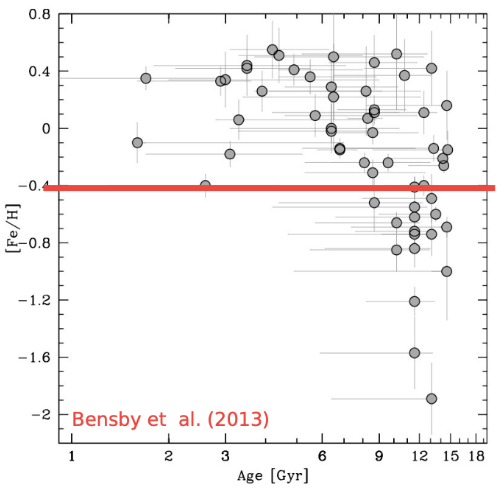


Figure 7.3: Stars with [Fe/H]≤ -0.4 are old, with ages of 10-12 Gyr while stars with [Fe/H]≥ -0.4 span a wide range of ages.

7.1.2 Formation of the bulge

Historically bulges and ellipticals are called spheroids: they share several properties (e.g. they lie in the same fundamental plane). Other bulges do not share these properties: they are called **pseudo-bulges**, look like **bars** and derived from **dynamical instability** of the disk.
There are two main approaches to investigate the formation of the bulge at high redshift:

1. **observations at high redshift** to see bulges in formation
2. **galactic archaeology**: investigation of the galactic bulge to map its structure, dynamics and stellar populations in great detail.

From the first approach we derived central concentration in massive galaxies at $z \sim 2$. In these objects star formation has almost ceased in the center but continues in the disk. Basically in these massive galaxies ($\log(M/M_\odot) > 11$), star formation is quenched from the inside out on time scales of less than 1 billion years (in the innermost region). These galaxies sustain high star-formation activity at large radii, while hosting fully grown and already quenched bulges in their cores. The total stellar mass and bulge mass grow synchronously in $z \sim 2$ galaxies. Their disks are in many aspects very different from those in the nearby universe: they have an higher gas fraction and are more compact for a given stellar mass. As a result of the higher gas content and density, the star formation rate at fixed stellar mass increases as $\sim (1+z)^{2.8}$.

There are various bulge formation scenarios.

1. Clumps Bulges are due to giant clump formation and their migration and coalescence to the center. To test this scenario we should see some residual gigantic clumps of star formation.

2. Disk instabilities Bulges form from the overall violent disk instabilities that lead to the central pileup of a large amount of star-forming gas with a very short depletion time.

In both scenarios bulges form rapidly out of the disk in a gas-rich dissipative environment.

3. Merging (classical bulges) Bulges form as a result of dissipationless merging of sub-units. In this scenario gravitational forces an torques disrupt the orbital paths of stars, resulting in the randomised bulge orbits. Hence they have properties similar to elliptical galaxies (stars with random orbits and spherical shape, distribution of light described by a Sersic profile).

4. Pseudo-bulges Bulges originates as a result of dissipationless bar formation in a gas-poor stellar disk with ensuing buckling instability of such a bar. Starting from a pure exponential stellar disk, N-body simulation predict that the disk develops a bar-forming instability and that, once formed, the bar is subject to buckling instability resulting in a cylindrical rotation and an x-shaped bulge.

7.1.3 Structure of the bulge

In the case of a classical bulge we expect a spherical shape and its luminosity would be characterized by a Sersic profile. In this scenario the number of stars for a fixed luminosity interval should be the same. This is not what happens in the MW: it was found that, for a fixed luminosity interval, stars at positive longitudes are more numerous and brighter (closer) than the ones at negative longitudes. This is an indicator of the fact that the GB is characterized by a **bar** with an inclination angle of ~ 25 degrees with respect to the Sun.

Effects of distance on the red clump If we take two CMDs of two identical stellar populations (same age and metallicity) but different distances we can see that the two CMDs are shifted one respect to the other in the vertical axis. It is difficult to distinguish the RGB of the two different populations due to observational errors but the red clump is a prominent feature. The splitting is similar to the one on the RGB but is more visible because red clump stars are brighter.
To easily identify the double red clump we can use the histogram plot: in this way in the location of the red clump we see a double peak.

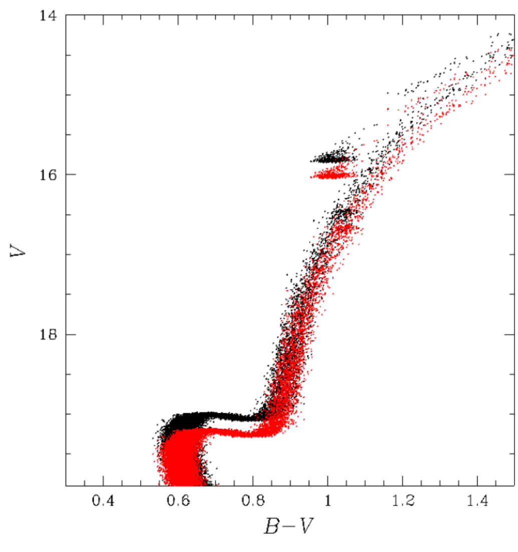


Figure 7.4: Double red clump

If we take a field far from the galactic plane we see that there is the bimodal distribution (black line in Fig. 7.5) while if we go closer to the galactic plane the bimodal distribution almost disappear (red histogram). We can do several observations and then plot the distribution of the distance inferred from the red clump as a function of the latitude. In this way we see that the GB is characterized by an x-shape.

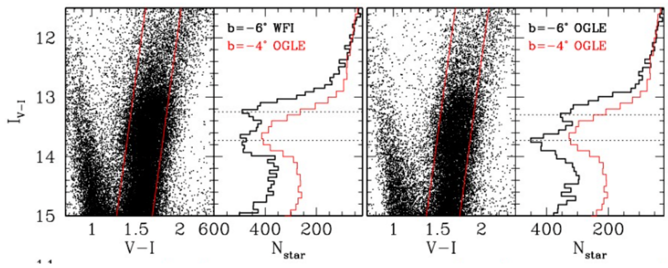


Figure 7.5: Evidences of the presence of the double peak in different fields of the GB.

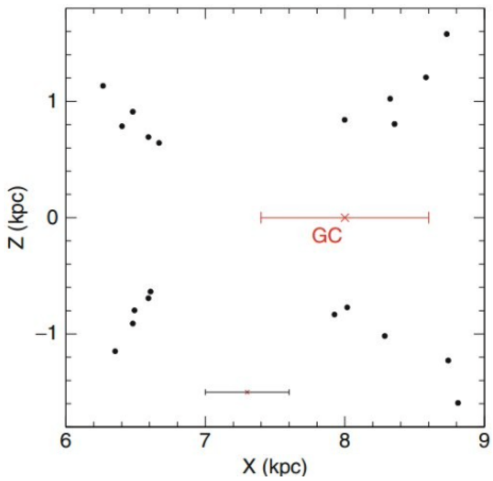


Figure 7.6: Plot that shows the shape of the GB. We expect the center to be at the center of the x but the deviation may be due to observational uncertainties.

Photometric metallicity map of the Galactic Bulge An alternative approach to investigate the structure of the GB is to look for stars with different metallicities. Remember that stellar populations that are metal rich have a redder RGB and a fainter turn off (entire CMD shifted to the red). Another quantity sensitive to the metallicity is the slope of the RGB: vertical for metal poor stars, kind of horizontal when we move to higher metallicities.
We simply need a photometric survey but we have observational challenges. If we take for example the Hess CMD (Fig. 7.7) taken with the ESO nIR survey (VVV) is impossible to derive information about stellar populations because of the differential reddening. It is possible to minimize the effect of the reddening using the red clump (we infer the amount of reddening in that part of the sky using the position of the red clump).
Comparing the CMDs of different regions of the sky, the color and magnitudes of stars change, exactly like the position of the red clump. In particular if we go from a region far from the galactic plane to a region that is closer we see that stars become fainter and redder.

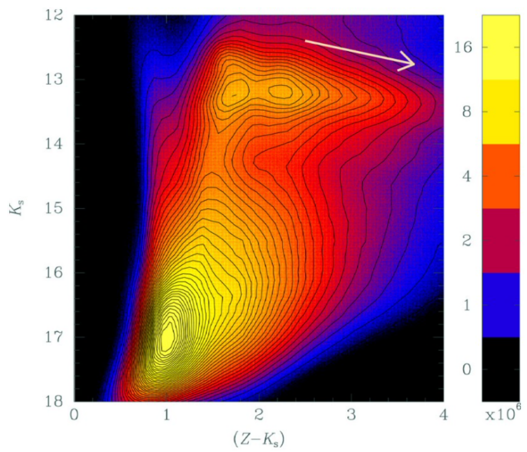


Figure 7.7: Hess CMD taken with the VVV. The white arrow points in the direction of the reddening, we have a broadened CMD in that direction.

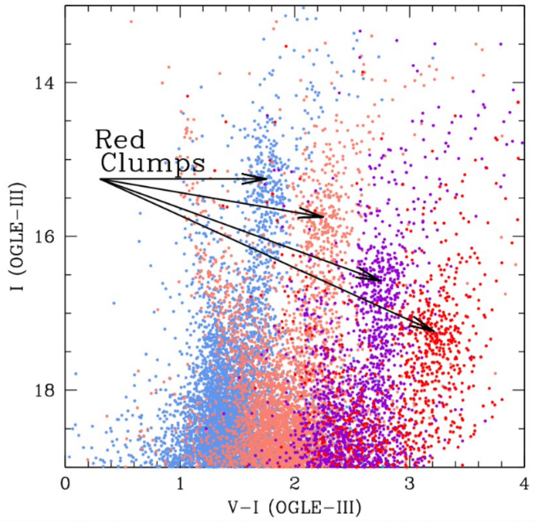
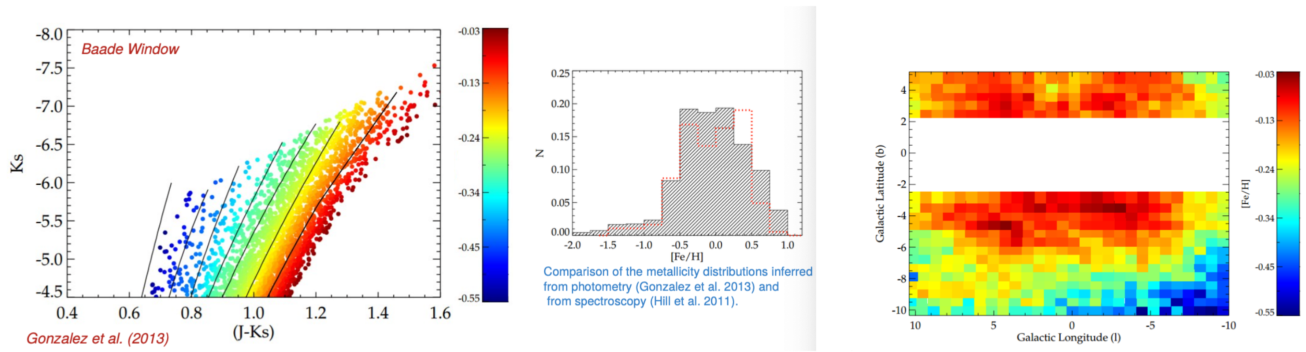


Figure 7.8: CMDs from different regions in the sky, we can see that the position of the red clump changes from one CMD to another. By comparing the positions of the red clump we can derive the direction of the reddening, and then a reddening map (totally empirical).

Comparing various CMDs (Fig. 7.8) we can constrain the reddening direction, hence the reddening law. Then we can correct the CMDs from VVV using this reddening law and derive the slope of the RGB of the different stellar populations, hence a complete metallicity map of the bulge (Fig. 7.9b).



(a) **(b)**

Figure 7.9: Different slopes of the RGBs due to different metallicities (a) and photometric metallicity map of the GB which reveals four lobes.

Studying stellar proper motions and radial velocities we can derive stellar orbits for faint and bright red clump stars. Bright RCs shows an excess of stars moving towards the Sun while an excess of stars receding from the Sun is seen in the far overdensity which is traced by fain red clump stars.
These stellar motions are consistent with predictions of dynamical models **peanut-shaped bulges**. The different motions of bright and faint red clump stars are explained by the presence of stars on elongated orbits which are most likely streaming along the arms of the x-shaped bulge.

X-shape component of the galactic bulge The X-shape is a natural dynamical process that happens to bar. Is due to the disk instability that drives stars to the center in elongated orbits. This process forms a bar, which is unstable: stars start buckling ending up in two families of stable orbits in shape of eight, banana or anti-banana.

The BRAVA survey BRAVA means bulge radial velocity assay ad is used to constrain the kinematic model of the GB. During this mission was found that the velocity dispersion of the stars in the GB is different when moving at different galactic longitudes: for a fixed latitude we have higher velocity dispersion when approaching the center of the galaxy. While moving far from the galactic plane, stars become kinematically hotter (higher velocity dispersion). This is what we expect when we have **cylindrical rotation**, which is one of the fingerprints of the scenario where the GB is characterized by a bar. In the case of a spheroidal distribution we expect a significant variation of rotation with latitude.
Cylindrical rotation confirms that we are in a **bulge-less body**.

Structure of the bulge from RR-Lyrae RR-Lyrae are variable stars that are present in old and metal poor populations. These stars are easy to be identified and, since their light curve is regular, they are standard candles used to derive the distance of the stellar population they belong to. by looking at the distribution of the stellar populations whose distance was derived with he RR-Lyrae we see that there is a huge discrepancy since these distribute as a spheroid. This may be due to the fact that RR-Lyrae trace metal poor population of the GB while the RC trace the metal-rich young population. These two populations follow different distributions.

Chemical abundances in the Galactic Bulge Papers based on high-resolution spectroscopy reveal that the Galactic Bulge is characterized by a wide spread in metallicity with a peak around solar metallicity and a tail towards lower [Fe/H]. This suggests an efficient star formation. There is an evidence for metallicity gradient along the minor axis of the bulge.
This bimodal distribution is consistent with most of the observed bulges. We have metal poor stars with a spheroidal velocity distribution and metal rich stars that evolve in an elongated (ellipsoid) velocity distribution. The metal poor population is more centrally concentrated than the metal rich one (in contrast with previous observations). For what concerns the density distribution we have 48% of metal poor component and 52% of metal rich.

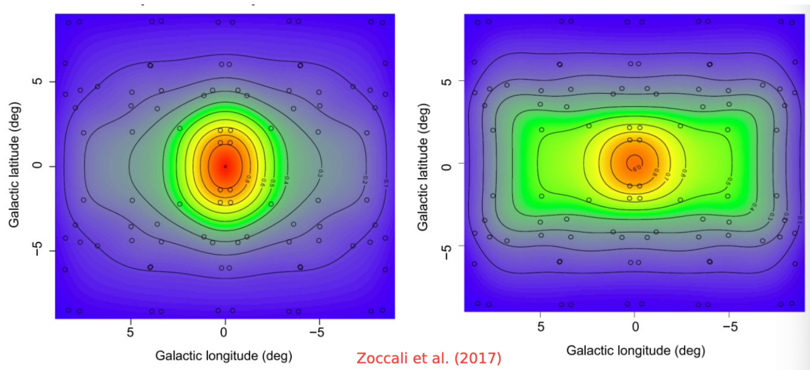


Figure 7.10: The metal poor component follows a spheroidal shape while the metal rich is distributed in a boxy-peanut shape.

We can say that the bar instability may have developed at a late time in the evolution of the Milky Way, while a bulge was already in place and formed at very early cosmic times.

7.2 The Disk

The disk of the Milky Way is the most active part (evolutionary activity) of the galaxy, contains a substantial fraction of the barionic mass of the MW and is composed by two structures: the **thin disk** and the **thick disk**, these features are visible if we get rid of the dust. The two component of the GD are characterized in terms of morphology by different scale-heights (shorter for the thin disk, longer for the thick). The thin disk is composed by blue stars, the thick by red ones. For this reason the thin disk is visible even with shorter exposure times. The different color of the stars can be associated to different ages of the stars and maybe at the same time different ages and metallicities.

7.2.1 Formation of the disk

There are two main different scenarios for the formation of the disk:

- The thin and thick disk in the MW are two real, separated entities. This scenario is consistent with models in which the thick disk is formed via an external mechanism like accretion and/or mergers.
- The thin and thick disk in the MW belong to the same structural entity. This is consistent internal dynamical evolution (radial mixing) and favors the scenario in which the thick disk is the evolutionary end point of an initially pure thin disk.

To investigate these formation scenarios we can use **kinematic** or **asteroseismology**.
By using the first method we have that, if the thin and the thick disk are two separated quantities, then we have different kinematic of the stars. Stars belonging to the thin disk are cooler, kinematically speaking, than stars belonging to the thick disk, which means that they have smaller vertical velocity wrt the galactic plane. Thick disk stars are also referred to as kinematically hot (higher galactic rotational velocity).
We can derive the RV dispersion for stars in the disk and we can compare it with the age of the corresponding stellar population. When doing so we see that old stars that seem to belong to the thick disk are characterized by higher

velocity dispersion than younger stars. So stars form in the thin disk and then migrate towards the thick disk. The age-velocity dispersion relation suggests a vertical age gradient.

An alternative technique is asteroseismology, which consists in measuring oscillations in the stars, which are sensitive to different parameters. One mission that uses this method is the secondary mission of Kepler (monitor variability of over 100000 stars). Asteroseismology allows us to determine fundamental physical quantities, including radii, distances and masses.

7.2.2 Structure of the disk

Vertical age structure of the Galactic Disk To derive the atmospheric parameters of the stars we can use photometry and spectroscopy, which deal with the same physics, combined with asteroseismology. We use the SAGA telescope to do photometry, which uses the Stroemgren photometric system. We observed the same stars in the field of view of Kepler and we inferred effective temperature, metallicity, gravity and other parameters. Low mass stars (RGB) dominate at increasing galactic heights, while closer to the galactic plane they exhibit a wide range of ages and metallicities.

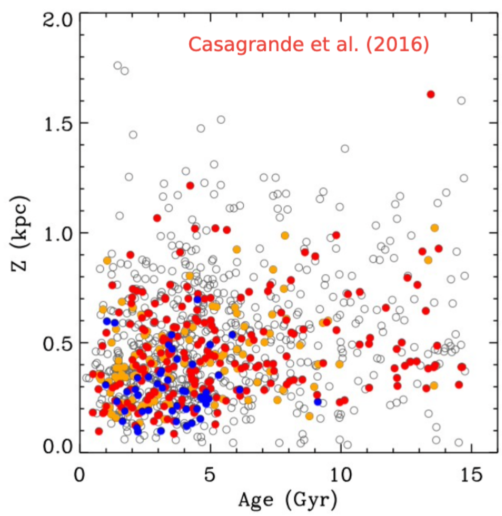


Figure 7.11: Relation between age and vertical distance of stars in the galactic disk.

Parametrizing the observations as a vertical gradient return approximately 4 Gyr/kpc for the disk. The ages of stars show a smooth distribution over the last 10 Gyr. There are evidences for a flat age-metallicity relation (Fig. 7.12) for the disk which is consistent with a mostly quiescent evolution for the Milky Way disk since a redshift of about 2.

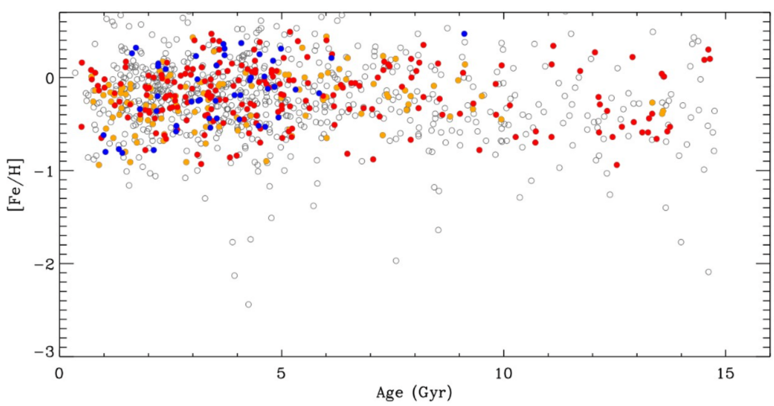


Figure 7.12: Age-metallicity relation for the disk.

For the spectroscopic analysis we used APOGEE which is an high resolution NIR spectroscopic survey of 50000 luminous Milky Way red giants. APOGEE and Gaia works together to provide age estimates for most stars.
When combining the information we obtain the plot in Fig. 7.13. If we plot an alpha element, like magnesium in this case we see a bimodal distribution. We have a "double" disk, whose components have distinct chemical composition,

ages and kinematics. In particular thin disk stars are observed to be on average more metal-rich and less alpha-enhanced than thick disk stars. We remember that alpha element are mostly produced by SN II so by massive stars that explode during the early stages of their life.

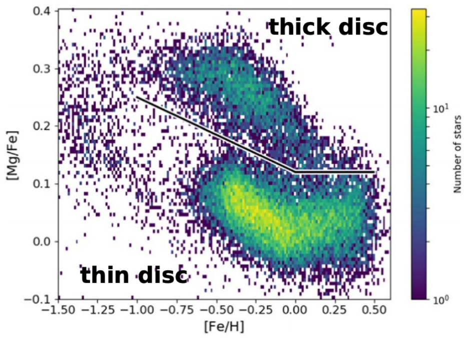
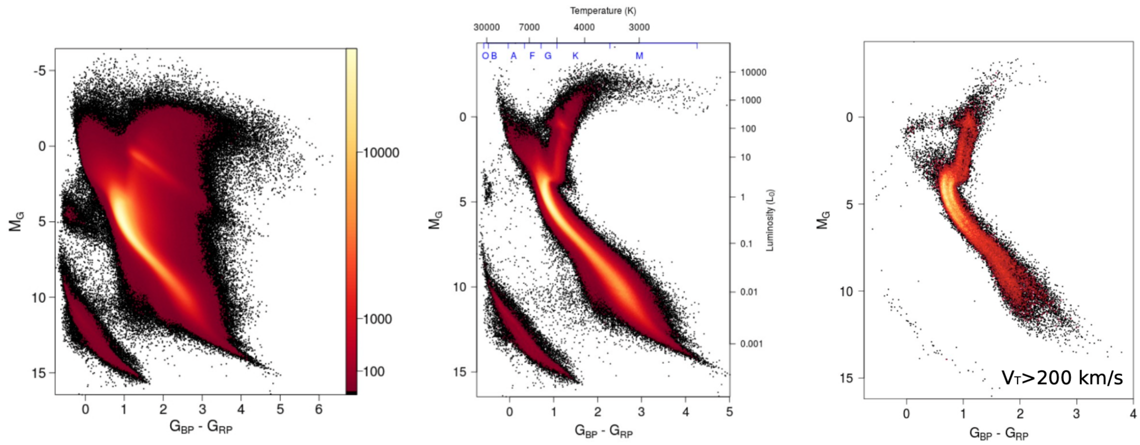


Figure 7.13: Combination of the results from Gaia, APOGEE and SAGA

In conclusion we have connections with Z, age and chemical composition so we can say that we have two distinct components: the thin and thick disk. One of the key points is the age gradient in the GD: stars at higher altitude are older than stars close to the plane. In addition we have also a radial age gradient: stars that are in the external part of the disk are younger. We can conclude that there is the phenomenon of migration of stars which is responsible for the age gradient and for the presence of thick and thin disk.

Gaia-Enceladus Sausage Using Gaia we derived the CMD of 66 000 000 stars. We can see that the MS of this CMD is shifted and extended due to differential reddening. After correcting for reddening (Fig. 7.14b) and selecting stars with high velocity ($v > 200\,\mathrm{km/s}$) we see that the CMD shows a split in the MS (Fig. 7.14c), so there are two different populations.



(a) (b) (c)

Figure 7.14: CMD from Gaia DR2. The first plot is the original one, the second one is the one corrected for reddening and the third is the one in which we selected only stars with high velocity.

This is not an effect associated to the reddening since we already choose only the low reddening stars. We can say that the galactic halo is composed by two different components, the inner and the outer halo. The split can be due to the metallicity variation.

So why do we have a thin and a thick disk in our galaxy? Analyzing the data from Gaia, and in particular the kinematics, we see that there is a significant fraction of stars, in blue in Fig. 7.15, that are linked to a single kinematic structure that a motion different from the motion of the majority of the stars of the MW and is retrograde. There are strong similarities with simulations of formation of a thick disk via a merger with another galaxy.
The large metallicity spread of the retrograde structure stars in the disk implies that they did not formed in a single burst. The fact that the Enceladus structure is characterized by low alpha abundances with respect to the thick disk for a fixed metallicity means that their stars formed in a stellar system where the star formation rate was lower than the thick disk. from the model of the chemical evolution is possible to derive the mass of GAIA-E at the formation,

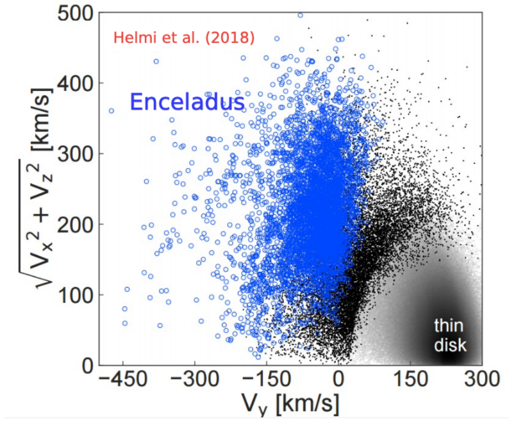
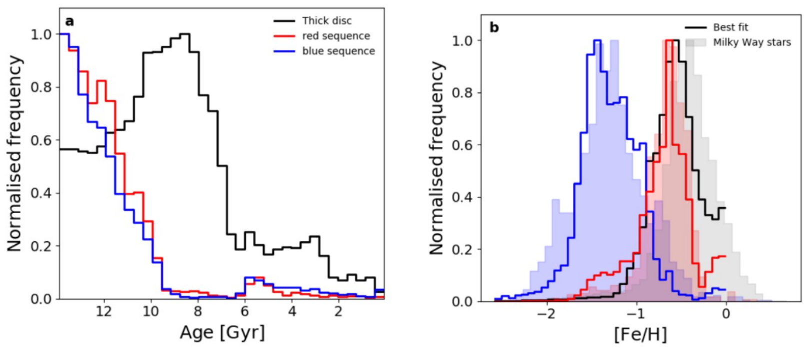


Figure 7.15: In blue the stars belonging to Enceladus, characterized by a slightly retrograde motion. This component dominates the CMD blue sequence revealed by the Gaia data.

so the mass of the progenitor, which was around $6 \cdot 10^8\,\mathrm{M}_\odot$. The structure had a mass comparable with the one of the MW at the moment of the merging.

Ages of the halo and the thick disk stars To derive the age of halo and thick disk stars we can take a combination of isochrones with different ages, metallicities and alpha elements abundances. Then we can derive some synthetic CMDs formed of multiple populations and compare them with the observed CMDs. In this way is possible to infer the precise star formation history of the stellar system. Once we have the precise chemical composition we can build the age distribution histogram, seen in Fig. 7.16a. In this case we see that stars in the blue and red sequences of the halo CMD are equally old and older than the bulk of thick disk stars. Doing the same analysis for the metallicity (Fig. 7.16b)we see that the red sequence host stars that formed within the seed progenitor of our MW (more metal rich), while the blue sequence host stars that originated in the lower mass galaxy Gaia-Enceladus.



(a) (b)

Figure 7.16: Age and metallicity distribution.

But which is the connection between this study about the halo and the disk of the MW? The merging process had some consequences on the formation and kinematics of the disk: the merging process was responsible for the heating of the primordial thin disk and the migration of the stars into the thick disk.

Sequoia From more accurate analysis of the data from GAIA DR2 they discovered other streams, like the Sequoia galaxy which is responsible for a major accretion episode, distinct from Gaia-Enceladus. The Sequoia event is, in particular, responsible for the bulk of high energy retrograde stars in the halo.

Chapter 8

The second parameter problem of the HB morphology

In the HB we have stars that produce energy burning He in the core and H in a shell. It is fundamental to understand the evolution of those stars because they represent one of the last stages of stellar evolution so understanding the HB means understanding what happens in white dwarfs.
Metallicity is considered the **first parameter** that determine the HB morphology: metal rich clusters are characterized by a red HB while metal poor ones have a bluer HB. However there are situations where globular clusters with the same metallicity have different HB morphologies. This is the **classical second parameter problem**.

As already said the structure of a star in the Horizontal Branch is characterized by an active He core and an envelope with an active H shell: the less massive the HB star, the less extended the envelope, the bluer it is.

A large variety of second parameters have been suggested: cluster age, ellipticity, mass, central concentration...

8.1 Global and non-global parameters

An approach is looking for multiple second parameters to determine the HB morphology. We have two main categories:

- a **global** parameter that is the same in one GC but varies from GC to GC;
- a **non-global** parameter that varies within the same GC.

To investigate this idea we introduce a new metric: we call L1 the color distance between the reddest part of the HB and the RGB and L2 the color extension of the HB.

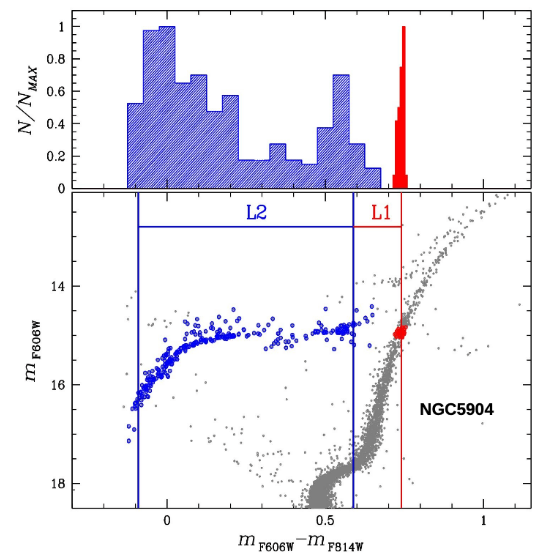


Figure 8.1: Parameters L1 and L2 highlighted in the CMD of the globular cluster NGC 5904.

We then analyze the behavior of these two parameters. **L1** depends on the **metallicity**, but this is not a single dependency: if we plot the parameter as a function of the metallicity we have three main groups, called G1, G2 and G3 as seen in Fig. 8.2. These groups are characterized by different values of the L1 parameter. In particular we have that G1 is the group of metal rich clusters, G2 are GCs for which L1< 0.4 (red HB) and G3 have L1> 0.4 (blue HB). This is just a confirmation of the dependence on the metallicity. We don't have any correlation between L1 and the mass or absolute luminosity but we have correlation with the age: clusters that are old are characterized by larger values of the L1 parameter.

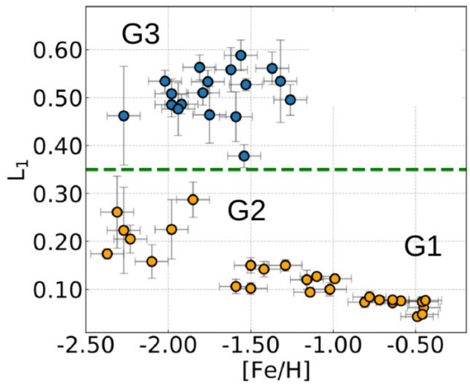


Figure 8.2: Correlation between metallicity and the L1 parameter.

What about the **L2** parameter?
If we plot L2 against metallicity or age there is no correlation at all, this is in contradiction with the fact that metallicity is the main parameter for the HB morphology.
We have correlation with the mass of the cluster, so with the absolute magnitude. We can conclude that the absolute magnitude is the second parameter.

8.2 Multiple populations and the second parameter

We know that GCs are composed by multiple stellar populations with different chemical composition. In particular if we consider that massive GCs exhibit large helium variations we can see if He abundance and L2 correlates. This is true so we can conclude that the second parameter of the HB morphology is Helium.
The location of a star on the HB is determined in first place by the **age** and **metallicity**, then for fixed age and metallicity the specific position of a star on the HB is determined by the **helium content** and the total amount of **mass lost** in the pre-HB stages.

Historically, helium and mass loss are considered degenerate quantities since we can reproduce nearly the same HB shape from different combinations of helium and mass loss.

We can conclude that L1 is governed by metallicity and age, while L2 depends on helium and mass loss. So **age** and **metallicity** are the main **global** parameters while the **range of helium abundance** and b within a GC are the main **non-global** parameters defining the HB morphology.

Chapter 9

Dwarf Galaxies

We can divide dwarf galaxies into two categories:

- **Dwarf Spheroidals (dSphs)**: low-luminosity galaxies of the local group, depleted in gas with little to no star formation. Usually associated with large galaxies.
- **Dwarf Irregulars (dIrrs)**: gas rich, star forming galaxies

Historically structural properties are used to distinguish dwarf galaxies from the other stellar systems and the presence of a dark matter halo is one of the most distinctive features. We can use a plane in which the x-axis is the absolute magnitude and the y-axis is the radius of the galaxy to distinguish the different classes of dwarf galaxies (Fig. 9.1).

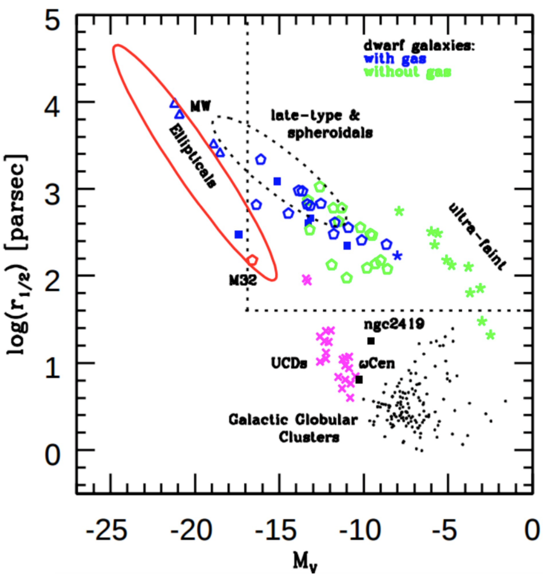


Figure 9.1: Plane used to distinguish the different classes of dwarf galaxies.

We want to understand the reason for such differences, so we need to address to morphological transformations.

9.1 Morphological transformations

Ram pressure The space between galaxies in a cluster is not empty: it is filled with superheated gas and plasma which drags and pulls galaxies as they move through it. The gas of the galaxy is stripped out.

Photo-evaporation The strong UV radiation coming from cosmic reionization can remove gas from the galaxy. For this reason the cosmic reionization is considered to be one of the main candidate responsible for the quenching of the star formation within the galaxy.

Stellar evolution Supernovae and stellar winds can inject kinetic energy in the surrounding gas, which can reach velocities sufficient to overpass the potential well of the galaxy, so the gas itself can escape the galaxy. SNe and stellar winds can be responsible for the quenching of the stellar formation.

Harassment Indicates the tidal interaction exerted by a major galaxy on an orbiting dwarf. It can result in a tidal stirring of the dwarf which, in extreme cases can also lead to tidal stripping and removal of the gas and consequently to the stop of the stellar formation.

9.2 Star formation history

To reconstruct the star formation history we can compare the observed CMD with a large number of simulated CMDs of simple stellar populations, then look for the combination of simple stellar populations that better reproduce the observed CMD provides the star formation history and the chemical evolution with time. Is important to remember that only appropriate regions of the CMD are used to compare the observations with the simulated CMDs.
Then form the SSP that compose the best-fit CMD is possible to infer the star-formation rate and the metallicity at different redshift.

From these kind of studies we can understand the role of the cosmic reionization in the star formation rate. We can investigate both true fossils and galaxies that are still forming stars. We investigate stellar clusters with a completeness higher than 90%, this means that at least the 90% of the stars has been measured. We can plot a 3D CMD (Fig. 9.2), in which we have on the z-axis how the star formation rate changes with time.

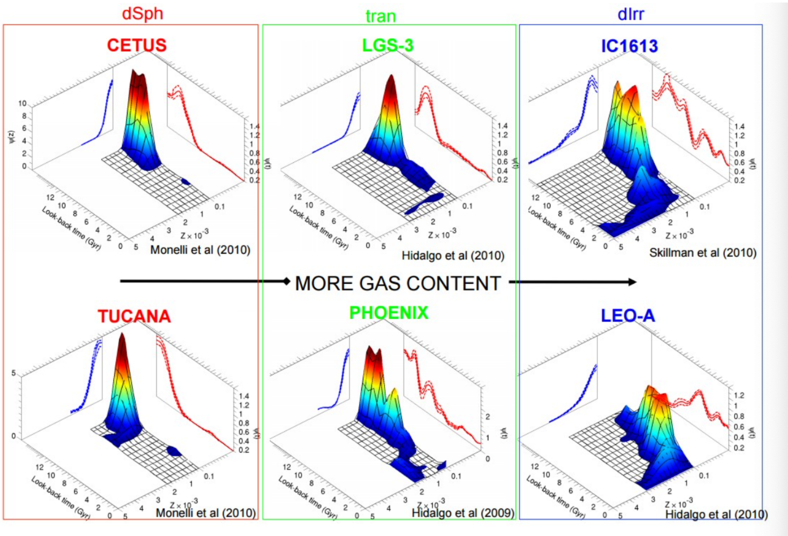


Figure 9.2: Three dimensional CMDs for three different kinds of dwarf galaxies.

In Fig. 9.2 we have three different kinds of dwarf galaxies: spheroidal dwarfs (no gas), irregular dwarfs (lots of gas) and transition dwarfs (medium gas content). In dSph we have that most of the stars formed a high redshift, but this changes when moving to dIrr through transition dwarfs. In particular dIrr are dominated by young stellar populations so a significant star formation history occurred at low z or present day.

9.3 Ultra-Compact Dwarfs (UCDs)

UCDs are quite a new class of stellar systems discovered in the core regions of nearby galaxy cluster. They are red in terms of color so they are characterized by old stellar populations. They appear similar to GCs but actually they are more massive, brighter and larger. They are even more compact than dwarf galaxies of comparable luminosity.

The proposed formation channels are:

- merging of stellar super-clusters;
- remnant nuclei of tidally stripped dwarf galaxies;
- most massive GCs of their host galaxy;
- genuine compact dwarf galaxies formed in the smallest peaks of primordial dark matter fluctuations.

There could be a connection between UCDs and Type II (anomalous) GCs, in which we have metallicity variations. Maybe these objects come from the same event but we don't know the nature of that event. Maybe they are something

similar to Sagittarius dwarf galaxy when merging with the Milky Way. In fact in the center of Sagittarius we have the stellar system M54 which looks like a UCD.
The main question is: are type II GCs the remnants of dwarf galaxies destroyed by tidal interaction with the Milky Way? Are they connected with UCDs?

Chapter 10

Dark Matter and Stellar Streams

The visible mass of the Milky Way is around $7 \cdot 10^{10}\,\mathrm{M}_\odot$ while the total mass is $1.5 \cdot 10^{12}\,\mathrm{M}_\odot$, this means that the 90%of the mass of the Milky Way is not visible. According to th ΛCDM model there are 10^4 subhalos in the MW with masses bigger than $10^7\,\mathrm{M}_\odot$. But how is it possible to study dark matter?
We can see if dark matter interact with ordinary matter (underground experiments), if dark matter interact with dark matter itself producing gamma rays (telescopes) or we can try to produce dark matter in laboratory. However none of these approaches provided solid results on dark matter interaction.

We can try to use **tides** and **stellar streams** to study the dark matter. We have that the gravitational pull of the MW creates tides. For example we can consider two clusters: the Pleiades and the Hyades. The ratio between the acceleration generated by the tides and the cluster itself is $\Delta a/a \sim 0.01$ for the Hyades and $\Delta a/a \sim 0.05$. These numbers are way bigger than the ones regarding the Earth and the Moon. When orbiting around the MW the globular cluster lose stars to form tidal streams in two specific directions. For example if we look at the GC Palomar 5 has a tidal stream of stars, as seen in Fig. 10.1.

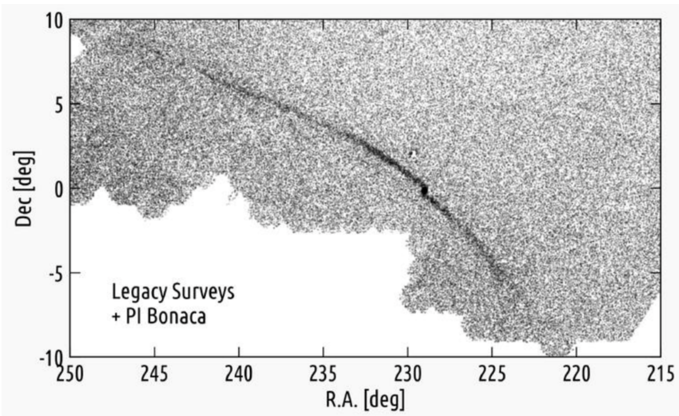


Figure 10.1: Tidal stream of stars of the globular cluster Palomar 5

Stellar streams preserve a **record of all gravitational interactions**. If we have a stellar stream in a smooth galaxy we expect that the distribution of stars in the stellar stream is kind of regular while if we have a galaxy where the distribution of dark matter is kind of clumpy then there is interaction between the DM clumps and the stars in the stellar stream, resulting in a stellar stream kind of clumpy.
We have to investigate the distribution of stars in real stellar streams to understand the distribution of dark matter in the galaxy.

10.1 Investigating stellar streams with GAIA

Using the data from GAIA DR2, corrected by proper motion and photometry we can identify with precision stars belonging to stellar streams. We see that the stream is characterized by a number of substructures, is not a continuous distribution of stars, we have a number of features and in particular we have two main gaps.
This means that the stellar stream has been perturbed, but who is this perturber? There are three main options:

- a globular cluster, an object composed of standard matter;

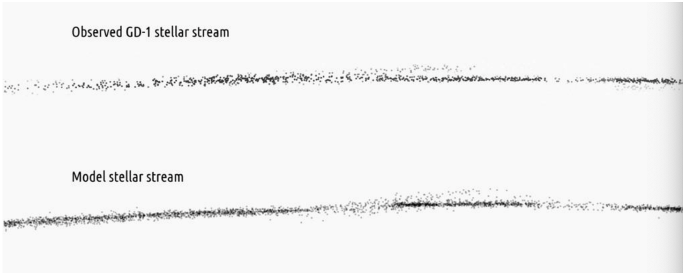


Figure 10.2: Stellar stream from GAIA DR2, the overall structure is the same but the observed stellar stream is clumpy.

- a point shaped object like a black hole;
- a dark matter clump.

The main properties we have to account to analyze the perturber are the mass, the distance and the size of the perturber itself.
We can try different combinations of these properties. Comparing the orbit of the stream with the orbit of a satellite of the MW we can see that the perturber is not a known satellite of the Milky Way. Based on the constraints we have that the perturber could be a dark matter subhalo, however the overlapping region is very small.

10.2 Modified Newton Dynamics (MOND)

The visible mass in galaxies and galaxy clusters is not sufficient to account for their dynamics when analyzed using Newton's laws. In particular this regards the discrepancy between the observed rotation curve and the predicted one. To solve this discrepancy, **Milgrom** suggested that the gravitational force experienced by a star in the outer region of a galaxy came to vary inversely with the radius (instead of the inverse square of the radius, as in Newton's law of gravity). In MOND the violation of Newton's laws occurs at extremely small accelerations, as those we expect in the outer region of the galaxy.

We can test the MOND theory using a particle in the outer part of the MW. For example we can use the GC NGC 2419. If we take the GC we can predict the dispersion of velocities of stars in the cluster as a function of the radius of the cluster. Depending on whether the system is described by Newton physics or MOND we expect different curves depending on the parameter k. However we have different results based on the distance we assume for the cluster.

Regardless our choice of the distance and our choice of the mass/luminosity ratio it is clear that the kinematics of stars in the cluster NGC 2419 are well fitted by the Newton theory and are hardly explained by the MOND theory.