Globular Clusters

Globular clusters (GCs) are aggregates of approximately 10^4–10^6 gravitationally bound stars, highly concentrated to the center, spread over a volume ranging from a few dozen up to more than 300 light-years (ly) in diameter. They resemble shining, old islands orbiting the Milky Way. As the name indicates, GCs show a largely spherical symmetry about their centers. A picture of the classic GC ω Centauri is shown in figure 1.

The stellar density in the cluster's center is so high (up to a few 10^3 stars ly^{-3}) that it is generally impossible to separate the individual stars from ground-based observations. Only recently has the refurbished Hubble Space Telescope (HST) allowed astronomers to dig into the very central regions of many Galactic globulars, where members (sometimes peculiar or even exotic) move randomly like molecules of gas, interacting according to the basic laws of gravity.

Early studies of GCs date back to the birth of modern astronomy. Since then, GCs have continued to offer excitement to both professional astronomers and sky-lovers with surprising results, and they constitute a basic benchmark for our astrophysical understanding.

The Milky Way hosts about 200 GCs. They form a halo of roughly spherical shape which is highly concentrated around the Galactic center, in the Sagittarius–Scorpius–Ophiuchus region. The most distant Galactic globulars (such as NGC 2419) are located far beyond the edge of the Galactic disk, at distances out to 300 000 ly.

RADIAL VELOCITY measurements have shown that most of the GCs are orbiting the Galaxy in highly eccentric elliptical orbits (see figure 2), with orbital periods of about 10^8 yr or even longer.

While following their orbits around the Galactic center, GCs are subject to a variety of perturbations (tidal forces from the parent galaxy, passage through the Galactic plane, star escape, internal dynamical evolution, etc) which make the existing GCs perhaps just the survivors of a much wider population, partially disrupted and spread out throughout the Galactic halo and far beyond. In this respect, it has been estimated that, within the next ten billion years or so, most of the present Galactic GCs could disappear. On the other hand, we know today that four clusters in Sagittarius (M54 in particular) are likely members of the Sagittarius Dwarf Elliptical Galaxy (discovered in 1994), currently merging into the central regions of the Milky Way.

A large majority of the galactic GCs have high relative velocities (100–300 km s^{-1}) with respect to the Sun, as they do not participate in the Galactic disk rotation. There is, however, a subsample, commonly referred to as 'disk globulars', which show properties closely connected to the disk.

Spectroscopic observations of stars in Galactic GCs have revealed that their chemical composition differs from that of the Sun in heavy elements content. GC stars are in fact typically metal poor and old. This is a signature that they were presumably born during the early stages of the Galaxy's formation and thus represent a sort of archeo-astronomical site where the universe in its youth can be studied.

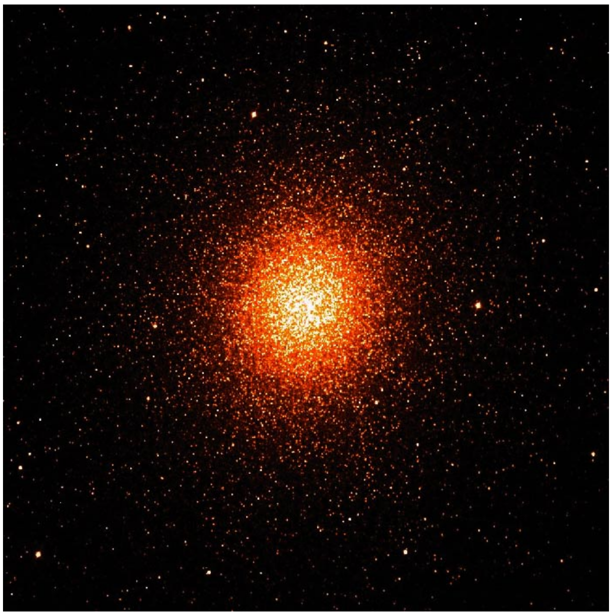

Figure 1. The GC ω Centauri.

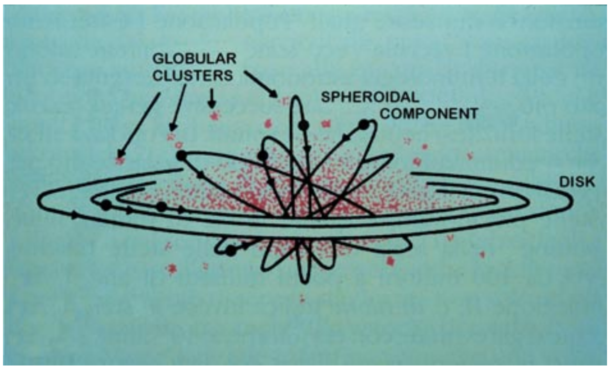

Figure 2. Orbits of GCs in the Galaxy.

Globular clusters seem to be ubiquitous. Edwin Hubble pioneered the search for globulars in the galaxies of the LOCAL GROUP with the detection of about 100 GCs in M31, the Andromeda Nebula (more than 350 GCs are known nowadays). However, it was only in the 1970s that the identification of any significant number of GC candidates became feasible around galaxies beyond the Local Group. The main reason for this difficulty in the search is that, with increasing distance, a typical cluster becomes progressively indistinguishable in shape from foreground stars or distant background galaxies.

It is now fairly well established that almost all galaxies have GC systems, in some cases (e.g. M87) containing several thousands of globulars (see GLOBULAR

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CLUSTER SYSTEMS IN NORMAL GALAXIES). There are, however, important differences. While all the globulars in our Galaxy and in M31 are old (ages of about 10 Gyr, at least), there are galaxies, such as the two Magellanic Clouds and M33 (the Triangulum Galaxy), hosting much younger GCs (ages of a few Gyr, or less).

The latest GC searches also reveal that dense, massive star clusters seem to be currently forming in the halos of some interacting galaxies (see GLOBULAR CLUSTER SYSTEMS IN INTERACTING GALAXIES). These objects are commonly interpreted as young and metal-rich GCs. This idea is not universally accepted, however. In fact, observational evidence, still quite meager, needs to be confirmed. Furthermore, astronomers seem somehow reluctant to change their traditional view of the GCs and to admit that massive, young and metal-rich GCs could possibly be even more frequent in the universe than the 'classic', ancient and very metal-poor ones.

Historical background

Perhaps the first historical detection of a globular cluster goes back to the mists of time, when human eyes first saw ω Centauri, the biggest Galactic GC, barely visible in the southern hemisphere.

The first 'astronomical' detection dates back to the 18th century. John Herschel, in the 1830s, realized that a large number of these clusters are concentrated in a relatively small portion of the sky in the direction of Sagittarius. Later on, HARLOW SHAPLEY detected variable stars in several GCs and, on the assumption they were Cepheids of known (calibrated) absolute magnitude, derived distances to them and to the Galactic center. Doing this, in 1917, Shapley understood that the Galactic center is located very far away from the Sun, in the direction of Sagittarius, and was also able to estimate the size of the Milky Way.

Today we know that Shapley significantly overestimated (by a factor of 2 or so) the size of the GCs system and of the Milky Way as a whole, mainly because the cluster variables he identified as Cepheids are actually RR Lyraes, whose absolute magnitude is about 2–4 mag fainter than Cepheids.

A key role in astronomy

Individual clusters as well as GC systems are of great worth as specific targets but also represent a powerful tool to obtain a deep insight into a large variety of astrophysical and cosmological problems (see table 1). Their study still represents a benchmark and a major field of interest in the international astronomical community.

Members of any given GC share a common history and differ one from another only in their initial mass. Consisting of a 'simple' STELLAR POPULATION (i.e. coeval, chemically homogeneous and isolated), GCs are ideal laboratories for testing the theories of stellar structure and evolution. In fact, thanks to the very large number of stars, almost every evolutionary stage (even those with very short lifetimes, down to a few 10^4 yr) is present at the appropriate statistical significance among the GC stars. This allows a direct check on the validity of the detailed evolution theory. When GCs are considered just as a million or so pointlike masses in a small volume, subject to internal and external dynamical interactions, they represent an ideal workbench to study STELLAR DYNAMICS and to test most exquisite theoretical dynamical models.

If studied as a global system, GCs constitute fossil tracers of the dynamical and chemical evolution of the parent galaxy and can be used as test particles to evaluate both the galaxy's total mass and its radial distribution.

GCs contain a variety of exciting objects by themselves worth a continuous investigation, for instance strong and weak x-ray sources, neutron stars and millisecond pulsars, white dwarfs, cataclysmic variables, binaries, blue stragglers, planetary nebulae, etc. Moreover, they contain one of the most popular intrinsic variable stars, the so-called RR LYRAE STARS. These stars have light variation amplitudes less than a couple of magnitudes and periods ranging from 0.2 to 1.1 days. Since their mean absolute magnitude is constant and fairly independent of metallicity (to within 0.3 mag), the RR Lyrae variables and the GCs, in turn, are ideal standard candles to measure distances.

Perhaps one of the most remarkable impacts of GC reasearch on other fields of astronomy is provided by the estimate of the ages of the Milky Way's globulars. GCs are, in fact, among the few objects in the Galaxy for which relatively precise ages can be derived. Since they are the oldest objects observed in the Milky Way so far, and were born during the very early stages of the Galaxy's formation, they provide a very stringent lower limit to the age of the universe. On the other hand, their age distribution and how ages vary with varying metallicity, spatial location in the Galaxy and kinematic properties make these systems direct tracers of the chronology of the first epoch of star formation in the Galactic halo and may help in understanding the whole process of galaxy formation.

Color–magnitude and Hertzsprung–Russell diagrams, and stellar evolution

The color–magnitude diagram (CMD) as well as its twin, the HERTZPRUNG–RUSSELL DIAGRAM (H–R diagram), substantially plot the temperature of a star on the X-axis, with increasing temperature to the left, and the star brightness on the Y-axis, with brighter stars at the top. Traditionally, the observational CMD reports on the X-axis the color of the stars (generally $B-V$) and on the Y-axis the observed apparent magnitude (generally V) or, if distance is known, the absolute magnitude (M_V).

The CMD is a basic, very powerful tool which allows a direct calibration of the observables in terms of fundamental intrinsic parameters (e.g. metallicity, age) as well as stringent comparisons to be made with theoretical model predictions (after 'tricky' transformations from the theoretical into the observational plane).

Figure 3(*a*) shows the observed CMD of the GC M3, and figure 3(*b*) displays the schematic CMD of a typical GC.

Table 1. Importance of GCs.

Subject	Reasons for importance
Witnesses of the early Galactic evolution	• First to form • Chemically uncontaminated
Stellar Evolution Laboratories	• Simple stellar populations • Test of the 'stellar clock'
Distance indicators	• Standard candles: the RR Lyrae stars • GC system integrated luminosity function
Age indicators	• The turn-off luminosity = 'the clock' absolute ages: lower limit to the age of the universe relative ages: 'second parameter' and Galaxy formation and evolution
Dynamics probes	• Dense environment core collapse evaporation collisions merging–surviving segregation • Test particle of the galactic gravitational field
Containers of peculiar objects	• X sources (strong–weak–diffuse) • Blue stragglers • Binaries • Planetary nebulae • White dwarfs • Cataclysmic variables • Millisecond pulsars • Neutron stars

Labels indicate the main branches of the diagram. The modern STELLAR EVOLUTION theory is able to predict quite precisely the physical processes undergone by stars which evolve along the CMD, and the whole evolutionary path of a Population II star is nicely described from the early to the final stages. Each specific evolutionary phase is labeled in figure 3(*b*), along with the corresponding basic nuclear burnings. A brief description of these main evolutionary stages is presented below.

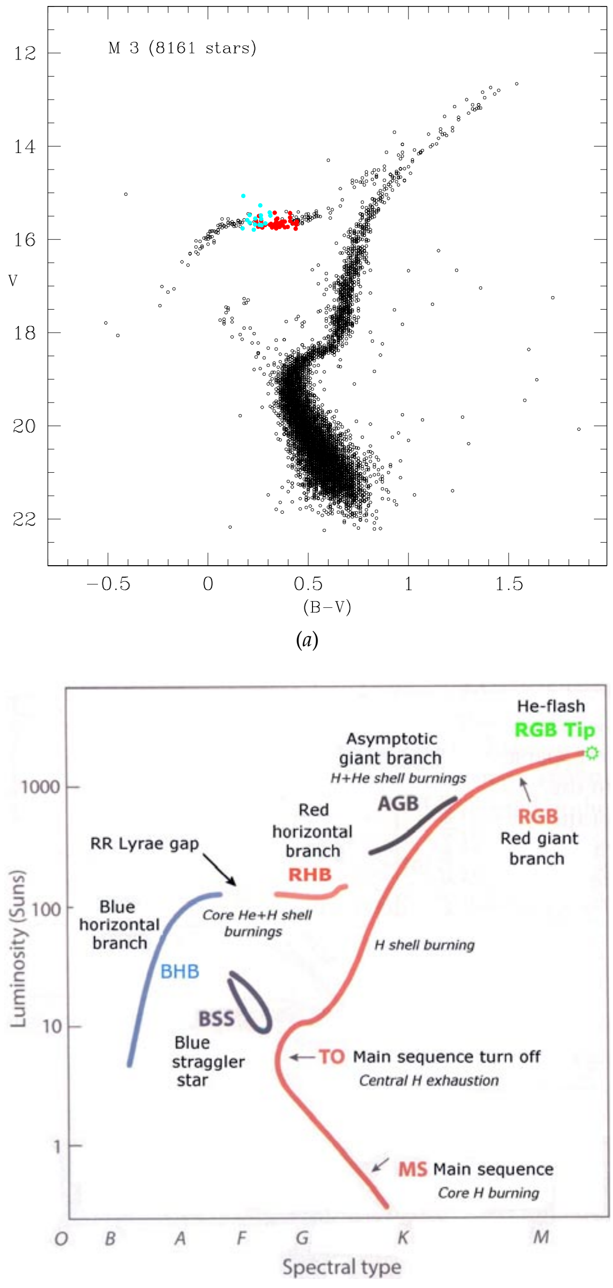
The evolutionary tracks drawn in the CMD by GC stars of given initial mass (below $1M_\odot$, actually $\sim 0.8M_\odot$) and chemical composition closely resemble the observed main ridge lines shown in figure 3(*b*). However, there is a fundamental difference. Each point of the evolutionary track is the locus reached by the same star at different ages during its evolution; conversely, each point on the observed CMD does indeed correspond to the locus of stars with same age and chemical composition, but different masses.

Given a collection of stars having the same chemical composition but different masses, each star will evolve along its evolutionary track, at its own evolutionary rate (depending on the star's mass). It will thus be possible to define loci of constant time along the various evolutionary tracks, which will yield constant-age sequences. These sequences are generally referred to as 'isochrones'. The isochrones thus represent the loci of stars with the same age and chemical composition, but with different masses. Since members of a GC can be thought of as being born from the same cloud at the same time, but with different masses, the comparison of theoretical isochrones (transformed into the observational plane) with the observed CMD is the key procedure to obtain information on the evolutionary status of GC stars.

The main sequence and the turn-off

After a free-fall phase, the gravitational contraction leads the proto-star to increase its central temperature until the ignition of the first nuclear reactions in the stellar core takes place. The nuclear energy production slows down and eventually stops the contraction. The star reaches a nice equilibrium, balancing energy production and transfer and global brightness, and enters into the main sequence (MS). This equilibrium holds on the MS for more than 70% of the total stellar lifetime ($\sim 10^{10}$ yr), until the nuclear fuel (hydrogen, i.e. 1 proton) in the very central core is completely burnt out. It should be recalled that there is a theoretical lower limit to the stellar mass ($\sim 0.08M_\odot$) below which H burning does not take place in the stellar core. Stars smaller than this threshold are usually called very low-mass (VLM) stars and brown dwarfs (BDs), and for masses far below this limit ($\sim 0.001M_\odot$) one has the giant planets.

Stars spend most of their lifetime quietly burning hydrogen in their core via nuclear fusion. Our Sun is still on the MS. As hydrogen gradually runs out in the center, a nucleus of helium (produced by the fusion of four protons) grows up, and the star core begins to contract owing to gravity, while the outer layers progressively expand and cool down. The star leaves the MS.



(*a*)

(*b*)

Figure 3. (*a*) Color–magnitude diagram of the globular cluster M3 and (*b*) schematic color–magnitude diagram of a typical globular cluster.

The central H exhaustion corresponds quite precisely to the bluest and hottest point on the MS, usually called the turn-off (TO) point. The precise location of the TO depends on the stellar initial mass, and theoretical models show that both luminosity and temperature of the TO increase with increasing stellar mass. Since, in turn, the initial mass depends on the age (stars burn out central H more and more slowly with decreasing mass), the TO is actually the 'stellar clock'. Turning to the isochrones, since less massive stars are still in the MS phase, while more massive ones are in more advanced evolutionary stages, the upper MS becomes more and more depleted with increasing age, while the TO becomes fainter and cooler. A straightforward relation can thus be derived between luminosity of the TO point and age. This relation provides a unique, powerful tool for determining the age of the GCs.

It should be pointed out that (a) the engine of the 'stellar clock' relies on theoretical models and (b) any method for dating stellar populations is finally founded on this 'stellar clock'. Were our understanding and running of this 'clock' incorrect, our description of the universe, as derived from the stars, would be in error. It should also be recalled that recent model calculations based on improved equation of state and radiative opacity, as well as the inclusion of element diffusion, have significant effects on both the luminosity of the TO, which is increased, and the MS lifetime, which is decreased with respect to previous 'classic' models.

Finally, the sharp MS TO observed in most clusters indicates that stars within individual GCs all formed roughly at the same time. The narrowness of the MS indicates that stars in a given GC all have very similar chemical composition, and also it constrains the fraction of binary stars within GCs. Unresolved binaries are in fact expected to produce a population just above the MS since the combined luminosity of the two stars exceeds that of a single star at the same color (see BINARY STARS IN GLOBULAR CLUSTERS).

The red giant branch

When the central fuel is exhausted, hydrogen starts burning in a thick shell which surrounds the growing helium core. A complex balancing between energy production and transfer, substantially driven by opacity, takes place. Core contraction and heating is accompanied by a progressive expansion of the outer envelope. The star cools down and brightens, owing to the larger and larger increase of the total radius, climbing along the red giant branch (RGB).

During this phase the deepening of the surface convection may reach the internal He-enriched zone and bring some extra helium to the stellar surface. All canonical computations confirm that, because of convective mixing phenomena (dredge-up) during the RGB phase, the surface He abundance exceeds the original He abundance. This increase of the He abundance may have important consequences in the subsequent evolutionary stages.

The comparison of the giant branches of different clusters has revealed that GCs of higher metallicity exhibit giant branches that are shallower and redder than those of low-metallicity clusters. The detailed astrophysics of the stars on the RGB is very complex, and the exact location of the RGB is dependent on details of the convective

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processes within such stars commonly treated using the so-called mixing length (l) theory.

At the tip of the RGB the temperature in the He-rich core has grown up enough (10^8 K) to ignite the central He burning, via the 3α reaction ($1\alpha = 1$ He nucleus $= 2$ protons + 2 neutrons). Contrary to most of the other evolutionary stages, this ignition occurs on a very short time-scale (a few years or even less), and it is thus often referred to as the 'He flash'.

The horizontal branch

After the He flash, the star quickly rearranges its structure and starts a quiescent He core burning phase, which will last for about 10^8 yr or so. In the CMD, the star jumps on the horizontal branch (HB) where the helium in the core is converted into carbon (C) and oxygen (O). Slightly afterwards, H burning re-ignites in a shell immediately outside the He core. The relative balancing between central He burning and H shell burning has important effects on both HB lifetime and star behavior.

The precise location in luminosity and temperature of a star which arrives on the so-called zero-age HB (ZAHB) is driven by (at least) three parameters: the chemical composition of the envelope, the size of the He core mass at the He flash and the mass of the envelope (which was generally affected by mass loss during the previous RGB phase).

At given metal abundance—the so-called 'first parameter'—and helium content, the ZAHB becomes bluer and bluer (i.e. hotter and hotter) with decreasing stellar envelope mass. In turn, the position taken on the ZAHB by a given GC star will depend on the amount of mass lost during the RGB phase; the larger the mass lost, the bluer the ZAHB location.

Given the absence of quantitative observational estimates and with the persistent lack of any reliable theory about mechanisms driving the mass loss, it is difficult to evaluate the amount of envelope actually lost by stars evolving along the RGB. To reproduce the observed HB morphologies (i.e. the color distribution of HB stars), it has become common procedure (a) to introduce a free parameter, which accounts for the whole mass loss process, and (b) to adopt an arbitrary dispersion in the total mass lost by individual stars. In fact, if no mass loss (or the same amount of mass loss) is assumed for stars of equal initial mass, the whole HB would collapse to a single clump, contrary to any observational evidence. Indeed, in order to reconcile theoretical He burning models with the color distribution of their observational counterparts, i.e. the HB stars in GCs, it seems conceivable that during the RGB phase stars lose up to $0.2M_\odot$ of their envelopes. However, mass loss affects only the very external layers of an RGB star, without altering the physical conditions in the core, where nuclear energy generation takes place.

Theoretical models show that both the ZAHB luminosity and the temperature location of the star on the ZAHB increase with increasing helium abundance Y, while both quantities decrease with increasing metal content Z. On the other hand, since with increasing age the initial mass decreases, at fixed total mass loss the HB distribution will become bluer and bluer with aging GCs. This property has a very deep impact on the description of formation and evolution of the Galaxy as in many studies the HB morphology is actually adopted as a 'secondary clock' (see below) for dating the GCs.

HB stars of appropriate mass may fall inside the so-called 'instability strip', also known as the 'RR Lyrae gap'. The envelopes of stars living inside or simply passing through this narrow region of the CMD (see figure 3(*b*)) become unstable for radial pulsation. The HB star thus becomes a variable of RR Lyrae type, so named from the historical prototype of this class of variables. The frequency of such stars in GCs is so high that the presence of RR Lyrae variables within the 'instability strip' of the HB is a well-defining feature of the population II stars. According to the periods of their RR Lyraes, Galactic globulars can be separated into two distinct subsets, the two Oosterhoff groups. It has been shown that the Oosterhoff separation, often referred to as the 'Oosterhoff effect', reflects a difference in the metal abundance of the host clusters, with variables in metal-poor clusters having longer mean periods than those in the metal-rich ones.

Since the HB is a bright and 'horizontal' feature of the CMD (hence, all its members have a very similar absolute magnitude), and since HB stars spend most of their HB lifetime at luminosities very close (0.1–0.2 mag) to their ZAHB luminosities, they are 'standard candles' to measure distances. RR Lyrae variables, in particular, are among the most used 'classic' standard candles of population II stellar systems. (See also HORIZONTAL-BRANCH STARS.)

The asymptotic giant branch and the white dwarfs

Eventually, when helium also vanishes in the central regions of the He core, the core contracts and He burning starts in a shell around it. The stellar structure, characterized at this stage by a carbon–oxygen core surrounded by a first He burning shell and by a second, more external, H burning shell, evolves upward in the CMD, asymptotically merging into the RGB during the asymptotic giant branch (AGB) phase.

Most AGB stars exhibit significant mass loss in the form of stellar winds, exactly in the same vein as shown while evolving along the brightest part of the RGB. Other peculiarities include He shell flashes, believed to be a consequence of the He burning shell being spatially thin, which can cause the star to migrate briefly to the instability strip and to mix burnt material into the outer layers. This results in significant peculiarities in the abundance of some chemical elements, whose detection and measurement offer important tests of the global evolutionary theory, including mass loss.

The normal AGB stage culminates, after the onset of thermal pulses and a phase of rapid mass loss or 'superwind', with the star blowing off its outer layers until all that is left is a central hot WHITE DWARF (WD) in the middle of a PLANETARY NEBULA.

Eventually, the white dwarf becomes faint and cools down, ending its evolution along the WD cooling line, a sequence almost parallel but about 4 mag fainter than the MS.

Blue stragglers

Discovered first in M3 more than 40 yr ago by Allan Sandage, and until recently just peculiar objects detected in only one or two clusters, a large number of BLUE STRAGGLERS (BSs) are being discovered nowadays by the HST observations of the central regions of almost any GC. Although all stars above a certain mass and luminosity in a given cluster are expected to have evolved off the MS, yet the BSs seem to sit nodding on the bright extension of the MS (see figure 3(*b*)), as if they were loitering on their evolutionary path compared with the other members of the cluster. Since BSs always seem to be more centrally concentrated than all other visible stars in a given cluster, their masses are expected to be significantly higher than either RGB or normal MS stars, and this would explain their brighter location along the extension of the MS. Since they are still not evolved, although more massive than the TO stars, one has to explain their origin, which is commonly associated with binaries. BSs could originate from collisions of individual stars in the very crowded central regions of the cluster or could be the merger product of primordial binaries. Some BSs have actually been found to be members of eclipsing binary systems.

Chemical composition

Galactic GCs are old, metal-poor population II stellar objects with metal abundances usually in the range -0.7 dex $<$ [Fe/H] $<$ -2.5 dex (where [Fe/H] $= \log(N_{\mathrm{Fe}}/N_{\mathrm{H}}) - \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\odot}$ and N is the number of atoms of the given element; our Sun has thus [Fe/H] $=$ 0.0). Although clusters almost as metal rich as the Sun (and perhaps even more) have been recently discovered near the Galactic center, the bulk of the GC population has metallicities around [Fe/H] $= -1.3$. The average metallicity of the GC system generally correlates with the total mass of the host galaxy; the bigger the galaxy, the richer the average GC.

A commonly accepted basic property of the stars in a given GC is that they all have about same age and chemical composition (at least primordial).

While no indication has ever been put forward for any age variation among stars of a single cluster, there is now gathering observational evidence that small differences in chemical composition are perhaps present. It is still a matter of debate whether they are primordial or due to evolution.

Besides the use of spectroscopic observations at intermediate and high resolution, direct information on the chemical properties of a given cluster can also be derived from its CMD. In fact, the location and intrinsic width of the main branches in the CMD both depend on chemical abundance. In particular, as a general rule, an increase in the helium fraction leads to bluer colors, while an increase of the metal content leads to redder colors. Moreover, any significant abundance spread yields a spread-out of the stars along the various branches with respect to the mean ridge line, which is different from one branch to another and increases with increasing abundance variation.

The observed color dispersion of the MS in the best-studied clusters implies upper limits to star-to-star variations in helium abundance of 0.03 dex (if dispersion is attributed to He variations only, but differential reddening, metallicity spreads, blending and intrinsic binarity may also contribute). This figure compares with an overall helium abundance of about 0.23–0.25 (mass fraction).

Similar reasoning can be applied to the giant branch. Here, since elements with low ionization potential such as Fe, Si and Mg significantly affect the opacity in the stellar envelopes, star-to-star variations would result in a color dispersion of the giants. Observations show that, with the exception of ω Cen which clearly displays a wide giant branch, compatible with abundance variations up to a factor of 10 at least, the vast majority of the Galactic GCs have quite narrow giant branches and, in turn, small intrinsic variations in the abundance of iron-peak elements.

Spectroscopy of giants is potentially a more powerful technique to detect metallicity variations. However, such observations require high resolution and are highly time consuming on large telescopes. The still poor samples already available actually confirm the general indications of the CMDs. Only ω Cen (the biggest and most elliptical Galactic GC) and perhaps M22 show a dispersion in [Fe/H].

One reason why metal homogeneity within GCs is so remarkable is that galaxies, including dwarf spheroidals of integrated luminosities comparable with GCs, all show quite wide dispersions in chemical abundances, suggesting that star formation probably occurred in a different way and that self-enrichment was at work much more efficiently.

Despite the homegeneity in [Fe/H] within stars of individual clusters, there are significant star-to-star variations in the abundances of other heavy elements. The best famous are the CN variations, known among GC stars for many years. The central question is whether these variations are primordial star-to-star differences built in when GCs formed or whether they result from stellar evolutionary processes.

Stellar evolution is expected to produce some abundance variations among stars at different evolutionary phases. If the convective envelope of an RGB star reaches sufficiently deep inside the star, it mixes material which underwent CNO processing up to the surface of the giant. This theoretical prediction is now supported by many observational results, although observational evidence would require more mixing than currently predicted by theory.

Other elements also exhibit abundance variations in the GCs. The [O/Fe] ratio in cluster giants sometimes shows considerable depletion compared with halo field stars, which are enhanced by a factor of several relative to the solar abundance. However, it is still not clear whether there is a real systematic ehnancement of [O/Fe] in GCs with respect to the solar fraction, and, if any, how it varies with varying total metal abundance. At present, metal-poor clusters with [Fe/H] = −2.0 dex seem to have approximately [O/Fe] = +0.3 dex, while this figure perhaps decreases to about 0 at [Fe/H] = −0.7 dex.

Finally, it should be mentioned that Al, Na and Mg show variations which seem to be hardly compatible with just evolutionary processes. In particular, Al and Na tend to be overabundant in GCs, show wide variations and are correlated with each other and anti-correlated with [O/Fe]. If these Al and Na variations are primordial, their anticorrelation with [O/Fe] suggests that CNO variations are also primordial, and this may have a deep impact on the description and understanding of star and cluster formation.

The horizontal branch morphology and the 'second parameter' problem

The color (temperature) distribution of the cluster stars along the HB is often referred to as the 'HB morphology' of the cluster. The number of stars within (V) and on both red (R) and blue (B) sides of the 'RR Lyrae gap' describes the overall HB morphology of a given cluster through the parameter

$$C = \frac{B - R}{B + V + R}.$$

Observations show that Galactic GCs exhibit a fairly broad variety of HB morphologies, with the C parameter ranging from −1.0, for clusters where only the red portion of the HB is populated, to +1.0, for clusters with stars only to the blue of the instability strip.

Since the color (temperature) of HB stars depends primarily on the stellar metal content—HB stars in metal-rich clusters are redder than those in metal-poor clusters as a result of the higher opacity in their envelopes and of higher initial masses (at fixed age)—metallicity is commonly considered the 'first parameter' driving the HB morphology.

However, metallicity variations alone cannot account for the extension in effective temperature and for the differences observed between HBs. In fact, were the HB morphology strictly driven just by metallicity, both the high chemical homegeneity among cluster members and the fine tuning of the TO masses would lead to a highly peaked clump of HB stars. The common evidence that most of the observed HBs display a wide coverage in color (only very metal-rich clusters show in fact a red stubby HB) suggests that mass loss affects in rather different ways GC stars of identical initial mass, no matter whatever mechanism(s) drives it.

On the other hand, although the HB morphology–metallicity correlation accounts for a large part of the observed HBs and most clusters exhibit a 'blueing' of their HBs with decreasing metal abundance, several other clusters do not obey this general rule. This is the essence of the long-standing historical 'second parameter problem': another parameter besides metallicity must be at work on the HB of the GCs.

Age, helium abundance and metal abundance ratios are the 'classical' second parameter candidates most often invoked to explain the observed HB morphologies.

Age has long been claimed to be the second parameter, but with no unanimous consensus among the astronomical community as not all second parameter clusters seem to be explicable in terms of age variations. Theoretical calculation shows that the average mass of a stars evolving onto the HB decreases with increasing cluster age. Since the He core mass is roughly constant for ages older than ∼10 Gyr, the mass of the envelope decreases with age. Hence, at fixed metallicity, older cluster ages would imply less massive HB stars, with increasingly thin evelopes and, in turn, bluer HBs. If age is the second parameter, the HB morphology could be used as a 'secondary clock', besides the TO luminosity, to test the existence of possible age gradients with varying distance from the Galactic center and the metallicity. This approach has been widely used in recent years to show that the GC system in the Milky Way is perhaps formed by different subgroups: (a) the halo GCs, possibly further subdivided into young and old, metal poor and spherically distributed throughout the wide halo; (b) the disk GCs, of intermediate metallicity, somehow kinematically related to the disk; (c) the bulge GCs, in general fairly metal rich (almost solar) and preferentially located in the central regions of the Galaxy; (d) the (possibly) captured GCs, originally members of disrupted or tidally interacting satellites of the Milky Way.

Variations in the helium content, with increasing helium abundance producing bluer HBs, could possibly explain some of the observed HB morphologies. On the other hand, also a variation in the CNO abundance (at fixed [Fe/H] content) would affect the HB morphology, with increasing CNO abundance yielding redder HBs, since elements of the CNO group directly control the opacity and energy generation within HB stars.

Also many other physical phenomena could affect the HB star properties. For instance, the stellar core rotation, if increased, would probably lead the star (a) to have a higher He core mass, consequently (b) to climb up brighter portions of the RGB and (c) if mass loss increases with increasing luminosity, as it appears to, to suffer in turn a larger mass loss, yielding bluer HBs.

Environmental conditions have also been shown to have some impact on the evolution of GC stellar populations. In particular, there are observational indications suggesting that higher cluster densities and concentrations would favor bluer HBs since stellar mass loss could be enhanced, because of the increased stellar interactions.

In conclusion, there is growing observational evidence that just a single 'second parameter' may be insufficient to explain the observed HBs and that a comprehensive understanding of the full range of the observed HB morphologies may require a ‘third parameter’, at least, although age is perhaps a dominant parameter in most GCs.

In this respect, a distinction could be made between a ‘global’ second parameter ruling the HB morphology and second parameters most likely determining the HB morphology of individual clusters. The former deals with the Milky Way globulars as a system and aims at describing the ‘global’ properties of the HB morphology compared with the other clusters of similar metallicity. In particular, it has been found that HB morphology correlates with Galactocentric distance, suggesting that the intrinsic quantity or phenomenon which causes the anomalous HB star distribution at that metallicity is also varying with varying cluster location within the Galaxy. Several authors have concluded that, of the various second parameter candidates, only age differences can reproduce the global second parameter effect and, at the same time, successfully reproduce the observed properties of RR Lyraes and the MS TOs. On the other hand, most observed HBs present special features (gaps, clumps, distortions) which naturally require the existence of ‘non-global’ effects, which relevance could also vary from star to star in a cluster.

In conclusion, any choice is uncertain at this stage, and the whole issue of the ‘second parameter’ effect is still matter of hot discussion and tireless study.

Absolute and relative ages

One of the most frequently asked questions in astronomy is, how old is the universe we live in? Since GCs (the most metal-poor ones, in particular) were formed during the very early times of the Galaxy, and represent the oldest stellar systems for which age can be estimated fairly accurately, their absolute ages set a very stringent lower limit on the universe’s age itself, since the universe cannot be younger than the oldest objects it contains.

The observational parameters required to estimate the absolute age of a given GC are the apparent magnitude and color of the TO, along with the distance to the cluster, its helium and metal content and the interstellar reddening along the line of sight. This allows the calculation of the absolute magnitude of the MS TO (the ‘observational stellar clock’). Once the absolute magnitude of the MS TO has been determined, ages can be estimated by comparison with appropriate model isochrones (the ‘theoretical clock’) properly transformed into the observational plane.

The primary source of uncertainty in the absolute ages derived from the luminosity of the MS TO is our poor knowledge about distances to clusters, although uncertainties in quantities such as metallicity, reddening and elemental abundance ratios must also be taken into account. It should be remembered that errors of 0.07 mag in the absolute luminosity of the MS TO or 0.01 mag in its color bring a corresponding error in the derived age of about 1 billion years.

Several methods exist to measure distances to GCs. Until recently, all of them were uncertain at about a 20% level. The effects of model uncertainties on the derived age estimates are more difficult to assess as they are dependent (with different weights) on parameters and calibrations which are not directly observable (reaction rates, opacities, treatments of convection and mixing, basic input physics, etc).

A recent attempt to quantitatively evaluate the global uncertainty of both observations and stellar models concluded that the age of the oldest clusters lies in the range 11–21 Gyr (Chaboyer *et al* 1996). These figures do not allow us to discriminate among different cosmological models.

Nearby subdwarfs, whose distances can be determined to high accuracy through trigonometric parallax, provide the best standard candles to estimate GC distances, especially after the results yielded by the ESA’s astrometrical satellite HIPPARCOS. The magnitude offset between the observed cluster MS and the absolute-calibrated MS of the local subdwarfs (assumed to be ‘bona fide’ representatives of GC subdwarfs of the same metal abundance) eventually gives the distance to the cluster.

Before HIPPARCOS, the available sample of local subdwarfs with known metallicity and accurate PARALLAXES was extremely poor. In early 1997, HIPPARCOS substantially increased the observational database, bringing the number of subdwarfs with very accurate parallaxes to about 900 stars, 30 of which have metallicities comparable with those of the GCs ([Fe/H] ≤ -1.0). The enlarged sample of subdwarfs and the use of new metal abundances in the same metallicity scale as used for GC stars have led to an almost halving of the uncertainty in derived cluster distances and, in turn, ages.

The discussion on the ages of the galactic GCs has been stirred up because of the global modifications of the astronomical distance scale implied by the HIPPARCOS results, which suggest that many Galactic objects, including the GCs, may be at distances about 10% larger from us than previously thought. The intrinsic luminosity of their TO stars should thus be about 20% brighter and they should also be roughly 15% younger, given the quoted relationship between TO luminosity and age.

The latest estimates yield therefore an age of 12–14 billion years for most of the GCs, and 13–14 billion years is perhaps the age of the most metal-poor and (presumably) oldest GC: M92.

An independent check of the distances derived from the subdwarf technique is absolutely necessary. A promising alternative is offered by the use of the WD cooling sequence. This technique relies on the matching of local WDs to WDs observed in GCs, as a matter of fact so exploiting, to a much fainter level, the same technique used with the subdwarfs. With the refurbished HST, it has become technically feasible to observe WDs in GCs. The first result from this technique for the GC NGC 6752 was obtained by Renzini *et al* in 1996. They find a distance consistent with other estimates, and derived ages of around 15 Gyr.

Although not totally incompatible, absolute ages derived for GCs in the pre-HIPPARCOS era were poorly consistent with most cosmological age determinations, such as those obtained through measurements of the Hubble constant. However, if the latest estimates of the GC ages obtained via HIPPARCOS parallaxes for the local subdwarfs are correct, the problems of the compatibility between the so-called 'stellar route' to cosmology and alternative routes are reduced, and would possibly disappear.

Relative ages of GCs are more reliable than absolute ages, primarily because determinations of age differences are less sensitive to stellar models and, second, and most important, because they do not depend on the assumed cluster distance. Their use allows one to address outstanding questions concerning the process of formation of our Galaxy. In particular, if we could define a reliable age–metallicity relation, as well as determine a variation of age with Galactocentric distance, we would be able to make a choice between the scenario suggested first by Eggen, Lynden-Bell and Sandage (1962), who think that the Galaxy was formed in a rapid, monolithic collapse (in a few 10^8 yr), and that proposed by Searle and Zinn (1978), who rather believe that the Galaxy formed much more gradually through the accretion of independent fragments (with masses ranging from $10^7 M_\odot$ up to $10^9 M_\odot$), over a few billion years or so. The detection of age differences among the Milky Way's GCs would in fact provide stringent constraints on the time scale and mechanism of formation of the Galactic halo.

Several methods have been employed so far to derive GC relative ages.

The most widely used technique exploits the difference in luminosity between MS TO and HB. Since the core mass of GC stars on the HB is roughly constant, the HB luminosity is almost independent of cluster age. On the contrary, the MS TO luminosity decreases with increasing the age, so the magnitude difference between the MS TO and the HB provides an estimate of the age of the GCs.

This method is elegant and simple in principle; however, it does suffer from several problems. The basic observational limitation is that while it works nicely for clusters having HBs well populated on both sides of the instability strip, it can hardly be applied when only red stubby HBs or just blue HB tails are present in the CMD. The latter case is particularly worrying since, if age is the second parameter, metal-poor clusters with blue HBs could be the oldest ones. A second basic problem is the still poor accuracy in our knowledge of the absolute magnitude of RR Lyrae stars (and thus of the HB (to yield absolute ages)) and of its dependence on metallicity.

The magnitude versus metallicity relation for RR Lyraes is usually described as: $M_V(\mathrm{RR}) = a[\mathrm{Fe/H}] + b$. The values currently obtained for a cover the range 0.15–0.35 mag dex^{-1}. This uncertainty is large enough to prevent any reliable determination of the GC age distribution since an error in the absolute magnitude of $\sim$0.20 mag implies a 2.5 Gyr error in the age. Furthermore, an estimate of the absolute age, with an error less than 1 Gyr, based on the RR Lyrae variables as absolute standard candles, requires knowledge of b to better than 0.07 mag.

The detailed comparison of the CMDs offers an alternative technique to deriving relative ages for GCs of similar metallicity. In fact, the relative distance of the clusters can be measured by simply superimposing the ridge lines of the main branches in the observed CMDs, after taking into account any differential interstellar reddening. If clusters of different metallicity are compared, further corrections (often uncertain) must be drawn from stellar atmosphere models. Once the best matching is achieved, however, the difference in the magnitude of the MS TO between the two compared clusters yields a straightforward measure of the age difference, if any.

Recent analyses of the relative ages of the best-observed Galactic GCs seem to indicate in general the existence of a small (less than 1 Gyr) spread. However, there is now also compelling evidence for larger age differences between some globulars. Probably the best-established cases are Ruprecht 106, Palomar 12, Terzan 7 and Arp 2. They (especially the first two) appear to be around 3 Gyr younger than other GCs of similar metallicity. It is unknown whether they are truly exceptions or whether other 'young' clusters lie still undetected. They could perhaps originally belong to a satellite galaxy tidally disrupted and captured by the Milky Way, but further confirmation is necessary.

In conclusion, the current status of our knowledge about the age of the Galactic GCs is consistent with an age distribution in which most Milky Way globulars are quite uniformally old (with ages of about 13 Gyr), and the oldest ones as old as 14 Gyr, but also with a few globulars significantly younger (by about 2–3 Gyr).

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