# 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 $\omega$ 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.

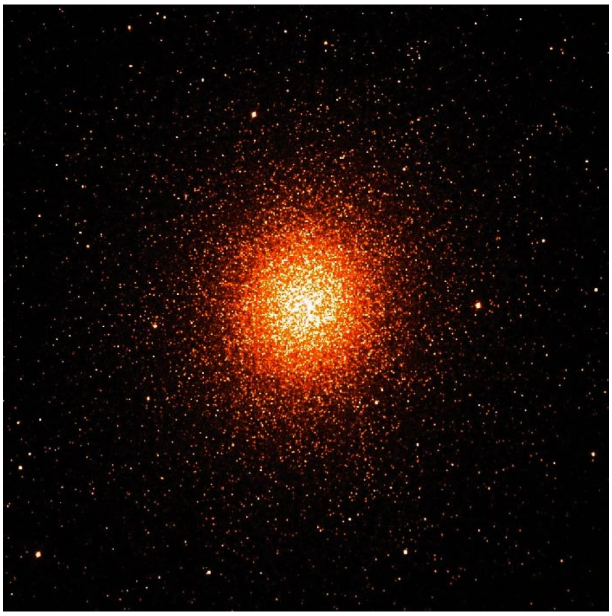

**Figure 1.** The GC $\omega$ Centauri.

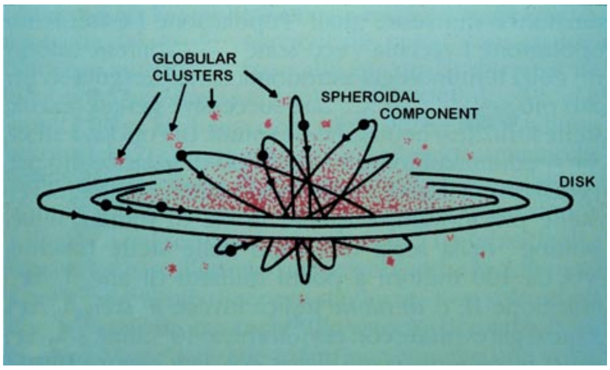

**Figure 2.** Orbits of GCs in the Galaxy.

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.

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

Brunel Road, Houndmills, Basingstoke, Hampshire, RG21 6XS, UK Registered No. 785998

Dirac House, Temple Back, Bristol, BS1 6BE, UK

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

Brunel Road, Houndmills, Basingstoke, Hampshire, RG21 6XS, UK Registered No. 785998
and Institute of Physics Publishing 2001
Dirac House, Temple Back, Bristol, BS1 6BE, UK

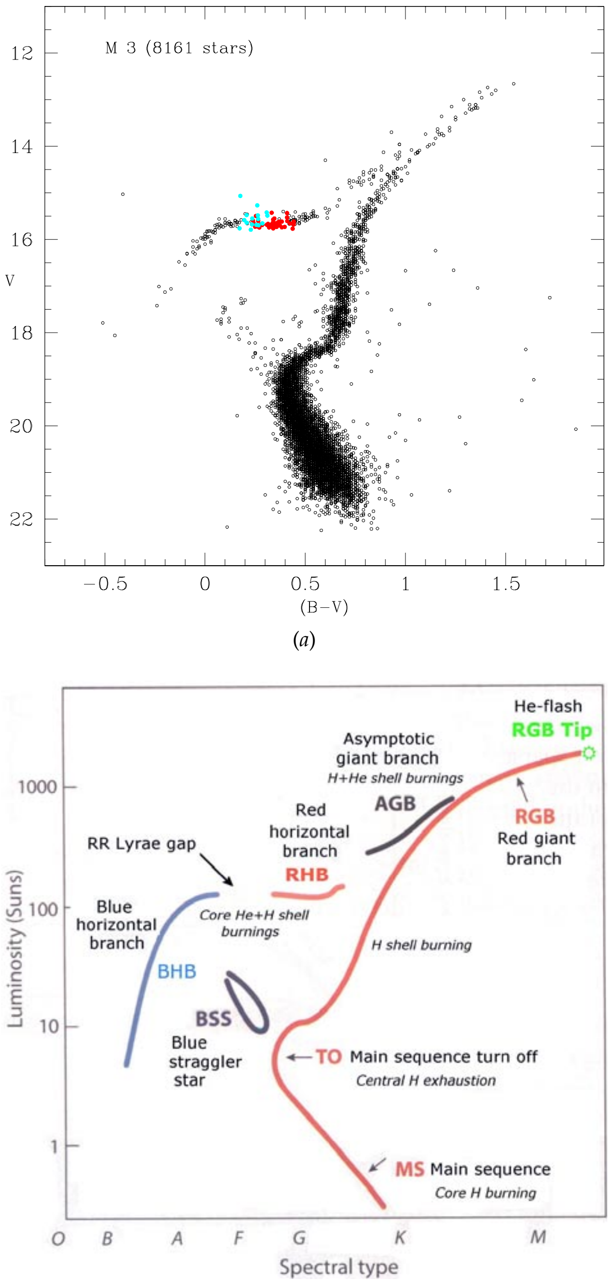

**Figure 3.** (*a*) Color–magnitude diagram of the globular cluster M3 and (*b*) schematic color–magnitude diagram of a typical globular cluster.

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

Brunel Road, Houndmills, Basingstoke, Hampshire, RG21 6XS, UK Registered No. 785998

Dirac House, Temple Back, Bristol, BS1 6BE, UK