= Globular cluster =

A globular cluster is a spherical collection of stars that orbits a galactic core as a satellite . Globular clusters are very tightly bound by gravity , which gives them their spherical shapes and relatively high stellar densities toward their centers . The name of this category of star cluster is derived from the Latin globulus ? a small sphere . A globular cluster is sometimes known more simply as a globular .

Globular clusters , which are found in the halo of a galaxy , contain considerably more stars and are much older than the less dense galactic , or open clusters , which are found in the disk . Globular clusters are fairly common ; there are about 150 to 158 currently known globular clusters in the Milky Way , with perhaps 10 to 20 more still undiscovered . These globular clusters orbit the Galaxy at radii of 40 kiloparsecs (130 @,@ 000 light @-@ years) or more . Larger galaxies can have more : Andromeda , for instance , may have as many as 500 . Some giant elliptical galaxies , particularly those at the centers of galaxy clusters , such as M87 , have as many as 13 @,@ 000 globular clusters .

Every galaxy of sufficient mass in the Local Group has an associated group of globular clusters , and almost every large galaxy surveyed has been found to possess a system of globular clusters . The Sagittarius Dwarf galaxy and the disputed Canis Major Dwarf galaxy appear to be in the process of donating their associated globular clusters (such as Palomar 12) to the Milky Way . This demonstrates how many of this galaxy 's globular clusters might have been acquired in the past .

Although it appears that globular clusters contain some of the first stars to be produced in the galaxy , their origins and their role in galactic evolution are still unclear . It does appear clear that globular clusters are significantly different from dwarf elliptical galaxies and were formed as part of the star formation of the parent galaxy rather than as a separate galaxy .

= = Observation history = =

The first globular cluster discovered was M22 in 1665 by Abraham Ihle , a German amateur astronomer . However , given the small aperture of early telescopes , individual stars within a globular cluster were not resolved until Charles Messier observed M4 . The first eight globular clusters discovered are shown in the table . Subsequently , Abbé Lacaille would list NGC 104 , NGC 4833 , M55 , M69 , and NGC 6397 in his 1751 ? 52 catalogue . The M before a number refers to the catalogue of Charles Messier , while NGC is from the New General Catalogue by John Dreyer .

When William Herschel began his comprehensive survey of the sky using large telescopes in 1782 there were 34 known globular clusters . Herschel discovered another 36 himself and was the first to resolve virtually all of them into stars . He coined the term " globular cluster " in his Catalogue of a Second Thousand New Nebulae and Clusters of Stars published in 1789 .

The number of globular clusters discovered continued to increase , reaching 83 in 1915 , 93 in 1930 and 97 by 1947 . A total of 152 globular clusters have now been discovered in the Milky Way galaxy , out of an estimated total of 180 ± 20 . These additional , undiscovered globular clusters are believed to be hidden behind the gas and dust of the Milky Way .

Beginning in 1914 , Harlow Shapley began a series of studies of globular clusters , published in about 40 scientific papers . He examined the RR Lyrae variables in the clusters (which he assumed were cepheid variables) and would use their period ? luminosity relationship for distance estimates . Later , it was found that RR Lyrae variables are fainter than cepheid variables , which caused Shapley to overestimate the distance to the clusters .

Of the globular clusters within the Milky Way , the majority are found in the vicinity of the galactic core , and the large majority lie on the side of the celestial sky centered on the core . In 1918 , this strongly asymmetrical distribution was used by Harlow Shapley to make a determination of the overall dimensions of the galaxy . By assuming a roughly spherical distribution of globular clusters around the galaxy 's center , he used the positions of the clusters to estimate the position of the sun relative to the galactic center . While his distance estimate was in significant error , it did demonstrate that the dimensions of the galaxy were much greater than had been previously thought

. His error was because dust in the Milky Way diminished the amount of light from a globular cluster that reached the earth , thus making it appear farther away . Shapley 's estimate was , however , within the same order of magnitude as the currently accepted value .

Shapley 's measurements also indicated that the Sun was relatively far from the center of the galaxy , contrary to what had previously been inferred from the apparently nearly even distribution of ordinary stars . In reality , ordinary stars lie within the galaxy 's disk and are thus often obscured by gas and dust , whereas globular clusters lie outside the disk and can be seen at much further distances .

Classification of globulars

Shapley was subsequently assisted in his studies of clusters by Henrietta Swope and Helen Battles Sawyer (later Hogg) . In 1927 ? 29 , Harlow Shapley and Helen Sawyer began categorizing clusters according to the degree of concentration the system has toward the core . The most concentrated clusters were identified as Class I , with successively diminishing concentrations ranging to Class XII . This became known as the Shapley ? Sawyer Concentration Class (it is sometimes given with numbers [Class 1 ? 12] rather than Roman numerals .) In 2015 , a new type of globular cluster was proposed on the basis of observational data , the dark globular clusters .

Formation

The formation of globular clusters remains a poorly understood phenomenon and it remains uncertain whether the stars in a globular cluster form in a single generation or are spawned across multiple generations over a period of several hundred million years . In many globular clusters , most of the stars are at approximately the same stage in stellar evolution , suggesting that they formed at about the same time . However , the star formation history varies from cluster to cluster , with some clusters showing distinct populations of stars . An example of this is the globular clusters in the Large Magellanic Cloud (LMC) that exhibit a bimodal population . During their youth , these LMC clusters may have encountered giant molecular clouds that triggered a second round of star formation . This star @-@ forming period is relatively brief , compared to the age of many globular clusters . It has also been proposed that the reason for this multiplicity in stellar populations could have a dynamical origin . In the Antennae galaxy , for example , the Hubble Space Telescope has observed clusters of clusters , regions in the galaxy that span hundreds of parsecs , where many of the clusters will eventually collide and merge . Many of them present a significant range in ages , hence possibly metallicities , and their merger could plausibly lead to clusters with a bimodal or even multiple distribution of populations .

Observations of globular clusters show that these stellar formations arise primarily in regions of efficient star formation , and where the interstellar medium is at a higher density than in normal star @-@ forming regions . Globular cluster formation is prevalent in starburst regions and in interacting galaxies . Research indicates a correlation between the mass of a central supermassive black holes (SMBH) and the extent of the globular cluster systems of elliptical and lenticular galaxies . The mass of the SMBH in such a galaxy is often close to the combined mass of the galaxy 's globular clusters .

No known globular clusters display active star formation , which is consistent with the view that globular clusters are typically the oldest objects in the Galaxy , and were among the first collections of stars to form . Very large regions of star formation known as super star clusters , such as Westerlund 1 in the Milky Way , may be the precursors of globular clusters .

Composition

Globular clusters are generally composed of hundreds of thousands of low @-@ metal , old stars . The type of stars found in a globular cluster are similar to those in the bulge of a spiral galaxy but confined to a volume of only a few million cubic parsecs . They are free of gas and dust and it is

presumed that all of the gas and dust was long ago turned into stars .

  Globular clusters can contain a high density of stars ; on average about 0 @.@ 4 stars per cubic parsec , increasing to 100 or 1000 stars per cubic parsec in the core of the cluster . The typical distance between stars in a globular cluster is about 1 light year , but at its core , the separation is comparable to the size of the Solar System (100 to 1000 times closer than stars near the Solar System) .

  However , they are not thought to be favorable locations for the survival of planetary systems . Planetary orbits are dynamically unstable within the cores of dense clusters because of the perturbations of passing stars . A planet orbiting at 1 astronomical unit around a star that is within the core of a dense cluster such as 47 Tucanae would only survive on the order of 108 years . There is a planetary system orbiting a pulsar (PSR B1620 ? 26) that belongs to the globular cluster M4 , but these planets likely formed after the event that created the pulsar .

  Some globular clusters , like Omega Centauri in the Milky Way and G1 in M31 , are extraordinarily massive , with several million solar masses (M ?) and multiple stellar populations . Both can be regarded as evidence that supermassive globular clusters are in fact the cores of dwarf galaxies that are consumed by the larger galaxies . About a quarter of the globular cluster population in the Milky Way may have been accreted along with their host dwarf galaxy .

  Several globular clusters (like M15) have extremely massive cores which may harbor black holes , although simulations suggest that a less massive black hole or central concentration of neutron stars or massive white dwarfs explain observations equally well .

= = = Metallic content = = =

  Globular clusters normally consist of Population II stars , which have a low proportion of elements other than hydrogen and helium when compared to Population I stars such as the Sun . Astronomers refer to these heavier elements as metals and to the proportions of these elements as the metallicity . These elements are produced by stellar nucleosynthesis and then are recycled into the interstellar medium , where they enter the next generation of stars . Hence the proportion of metals can be an indication of the age of a star , with older stars typically having a lower metallicity .

  The Dutch astronomer Pieter Oosterhoff noticed that there appear to be two populations of globular clusters , which became known as Oosterhoff groups . The second group has a slightly longer period of RR Lyrae variable stars . Both groups have weak lines of metallic elements . But the lines in the stars of Oosterhoff type I (OoI) cluster are not quite as weak as those in type II (OoII) . Hence type I are referred to as " metal @-@ rich " (e.g. Terzan 7) while type II are " metal @-@ poor " (e.g. ESO 280 @-@ SC06) .

  These two populations have been observed in many galaxies , especially massive elliptical galaxies . Both groups are nearly as old as the universe itself and are of similar ages , but differ in their metal abundances . Many scenarios have been suggested to explain these subpopulations , including violent gas @-@ rich galaxy mergers , the accretion of dwarf galaxies , and multiple phases of star formation in a single galaxy . In the Milky Way , the metal @-@ poor clusters are associated with the halo and the metal @-@ rich clusters with the bulge .

  In the Milky Way it has been discovered that the large majority of the low metallicity clusters are aligned along a plane in the outer part of the galaxy 's halo . This result argues in favor of the view that type II clusters in the galaxy were captured from a satellite galaxy , rather than being the oldest members of the Milky Way 's globular cluster system as had been previously thought . The difference between the two cluster types would then be explained by a time delay between when the two galaxies formed their cluster systems .

= = = Exotic components = = =

  Globular clusters have a very high star density , and therefore close interactions and near @-@ collisions of stars occur relatively often . Due to these chance encounters , some exotic classes of stars , such as blue stragglers , millisecond pulsars and low @-@ mass X @-@ ray binaries , are

much more common in globular clusters . A blue straggler is formed from the merger of two stars , possibly as a result of an encounter with a binary system . The resulting star has a higher temperature than comparable stars in the cluster with the same luminosity , and thus differs from the main sequence stars formed at the beginning of the cluster .

Astronomers have searched for black holes within globular clusters since the 1970s . The resolution requirements for this task , however , are exacting , and it is only with the Hubble space telescope that the first confirmed discoveries have been made . In independent programs , a 4 @,@ 000 M ? intermediate @-@ mass black hole has been suggested to exist based on HST observations in the globular cluster M15 and a 20 @,@ 000 M ? black hole in the Mayall II cluster in the Andromeda Galaxy . Both x @-@ ray and radio emissions from Mayall II appear to be consistent with an intermediate @-@ mass black hole .

These are of particular interest because they are the first black holes discovered that were intermediate in mass between the conventional stellar @-@ mass black hole and the supermassive black holes discovered at the cores of galaxies . The mass of these intermediate mass black holes is proportional to the mass of the clusters , following a pattern previously discovered between supermassive black holes and their surrounding galaxies .

Claims of intermediate mass black holes have been met with some skepticism . The heaviest objects in globular clusters are expected to migrate to the cluster center due to mass segregation . As pointed out in two papers by Holger Baumgardt and collaborators , the mass @-@ to @-@ light ratio should rise sharply towards the center of the cluster , even without a black hole , in both M15 and Mayall II .

= = Color @-@ magnitude diagram = =

The Hertzsprung @-@ Russell diagram (HR @-@ diagram) is a graph of a large sample of stars that plots their visual absolute magnitude against their color index . The color index , B ? V , is the difference between the magnitude of the star in blue light , or B , and the magnitude in visual light (green @-@ yellow) , or V. Large positive values indicate a red star with a cool surface temperature , while negative values imply a blue star with a hotter surface .

When the stars near the Sun are plotted on an HR diagram , it displays a distribution of stars of various masses , ages , and compositions . Many of the stars lie relatively close to a sloping curve with increasing absolute magnitude as the stars are hotter , known as main @-@ sequence stars . However the diagram also typically includes stars that are in later stages of their evolution and have wandered away from this main @-@ sequence curve .

As all the stars of a globular cluster are at approximately the same distance from us , their absolute magnitudes differ from their visual magnitude by about the same amount . The main @-@ sequence stars in the globular cluster will fall along a line that is believed to be comparable to similar stars in the solar neighborhood . The accuracy of this assumption is confirmed by comparable results obtained by comparing the magnitudes of nearby short @-@ period variables , such as RR Lyrae stars and cepheid variables , with those in the cluster .

By matching up these curves on the HR diagram the absolute magnitude of main @-@ sequence stars in the cluster can also be determined . This in turn provides a distance estimate to the cluster , based on the visual magnitude of the stars . The difference between the relative and absolute magnitude , the distance modulus , yields this estimate of the distance .

When the stars of a particular globular cluster are plotted on an HR diagram , in many cases nearly all of the stars fall upon a relatively well defined curve . This differs from the HR diagram of stars near the Sun , which lumps together stars of differing ages and origins . The shape of the curve for a globular cluster is characteristic of a grouping of stars that were formed at approximately the same time and from the same materials , differing only in their initial mass . As the position of each star in the HR diagram varies with age , the shape of the curve for a globular cluster can be used to measure the overall age of the star population .

However , the above @-@ mentioned historic process of determining the age and distance to globular clusters is not as robust as first thought , since the morphology and luminosity of globular

cluster stars in color @-@ magnitude diagrams are influenced by numerous parameters , many of which are still being actively researched . Certain clusters even display populations that are absent from other globular clusters (e.g. , blue hook stars) , or feature multiple populations . The historical paradigm that all globular clusters consist of stars born at exactly the same time , or sharing exactly the same chemical abundance , has likewise been overturned (e.g. , NGC 2808) . Further , the morphology of the cluster stars in a color @-@ magnitude diagram , and that includes the brightnesses of distance indicators such as RR Lyrae variable members , can be influenced by observational biases . One such effect is called blending , and it arises because the cores of globular clusters are so dense that in low @-@ resolution observations multiple (unresolved) stars may appear as a single target . Thus the brightness measured for that seemingly single star (e.g. , an RR Lyrae variable) is erroneously too bright , given those unresolved stars contributed to the brightness determined . Consequently , the computed distance is wrong , and more importantly , certain researchers have argued that the blending effect can introduce a systematic uncertainty into the cosmic distance ladder , and may bias the estimated age of the Universe and the Hubble constant .

The most massive main @-@ sequence stars will also have the highest absolute magnitude , and these will be the first to evolve into the giant star stage . As the cluster ages , stars of successively lower masses will also enter the giant star stage . Thus the age of a single population cluster can be measured by looking for the stars that are just beginning to enter the giant star stage . This forms a " knee " in the HR diagram , bending to the upper right from the main @-@ sequence line . The absolute magnitude at this bend is directly a function of the age of globular cluster , so an age scale can be plotted on an axis parallel to the magnitude .

In addition , globular clusters can be dated by looking at the temperatures of the coolest white dwarfs . Typical results for globular clusters are that they may be as old as 12 @.@ 7 billion years . This is in contrast to open clusters which are only tens of millions of years old .

The ages of globular clusters place a bound on the age limit of the entire universe . This lower limit has been a significant constraint in cosmology . Historically , astronomers were faced with age estimates of globular clusters that appeared older than cosmological models would allow . However , better measurements of cosmological parameters through deep sky surveys and satellites such as the Hubble Space Telescope appear to have resolved this issue .

Evolutionary studies of globular clusters can also be used to determine changes due to the starting composition of the gas and dust that formed the cluster . That is , the evolutionary tracks change with changes in the abundance of heavy elements . The data obtained from studies of globular clusters are then used to study the evolution of the Milky Way as a whole .

In globular clusters a few stars known as blue stragglers are observed , apparently continuing the main sequence in the direction of brighter , bluer stars . The origins of these stars is still unclear , but most models suggest that these stars are the result of mass transfer in multiple star systems .

= = Morphology = =

In contrast to open clusters , most globular clusters remain gravitationally bound for time periods comparable to the life spans of the majority of their stars . However , a possible exception is when strong tidal interactions with other large masses result in the dispersal of the stars .

After they are formed , the stars in the globular cluster begin to interact gravitationally with each other . As a result , the velocity vectors of the stars are steadily modified , and the stars lose any history of their original velocity . The characteristic interval for this to occur is the relaxation time . This is related to the characteristic length of time a star needs to cross the cluster as well as the number of stellar masses in the system . The value of the relaxation time varies by cluster , but the mean value is on the order of 109 years .

Although globular clusters generally appear spherical in form , ellipticities can occur due to tidal interactions . Clusters within the Milky Way and the Andromeda Galaxy are typically oblate spheroids in shape , while those in the Large Magellanic Cloud are more elliptical .

= = = Radii = = =

 Astronomers characterize the morphology of a globular cluster by means of standard radii . These are the core radius (rc) , the half @-@ light radius (rh) , and the tidal (or Jacobi) radius (rt) . The overall luminosity of the cluster steadily decreases with distance from the core , and the core radius is the distance at which the apparent surface luminosity has dropped by half . A comparable quantity is the half @-@ light radius , or the distance from the core within which half the total luminosity from the cluster is received . This is typically larger than the core radius .

 Note that the half @-@ light radius includes stars in the outer part of the cluster that happen to lie along the line of sight , so theorists will also use the half @-@ mass radius (rm) ? the radius from the core that contains half the total mass of the cluster . When the half @-@ mass radius of a cluster is small relative to the overall size , it has a dense core . An example of this is Messier 3 (M3) , which has an overall visible dimension of about 18 arc minutes , but a half @-@ mass radius of only 1 @.@ 12 arc minutes .