= 18 pc) and Palomar 14 (Rh =
25 pc)) .

Finally the tidal radius , or Hill sphere , is the distance from the center of the globular cluster at which the external gravitation of the galaxy has more influence over the stars in the cluster than does the cluster itself . This is the distance at which the individual stars belonging to a cluster can be separated away by the galaxy . The tidal radius of M3 is about 40 arc minutes , or about 113 pc at the distance of 10 @.@ 4 kpc .

= = = Mass segregation , luminosity and core collapse = = =

In measuring the luminosity curve of a given globular cluster as a function of distance from the core , most clusters in the Milky Way increase steadily in luminosity as this distance decreases , up to a certain distance from the core , then the luminosity levels off . Typically this distance is about 1 ? 2 parsecs from the core . However about 20 % of the globular clusters have undergone a process termed " core collapse " . In this type of cluster , the luminosity continues to increase steadily all the way to the core region . An example of a core @-@ collapsed globular is M15 .

Core @-@ collapse is thought to occur when the more massive stars in a globular cluster encounter their less massive companions . Over time , dynamic processes cause individual stars to migrate from the center of the cluster to the outside . This results in a net loss of kinetic energy from the core region , leading the remaining stars grouped in the core region to occupy a more compact volume . When this gravothermal instability occurs , the central region of the cluster becomes densely crowded with stars and the surface brightness of the cluster forms a power @-@ law cusp . (Note that a core collapse is not the only mechanism that can cause such a luminosity distribution ; a massive black hole at the core can also result in a luminosity cusp .) Over a lengthy period of time this leads to a concentration of massive stars near the core , a phenomenon called mass segregation .

The dynamical heating effect of binary star systems works to prevent an initial core collapse of the cluster . When a star passes near a binary system , the orbit of the latter pair tends to contract , releasing energy . Only after the primordial supply of binaries is exhausted due to interactions can a deeper core collapse proceed . In contrast , the effect of tidal shocks as a globular cluster repeatedly passes through the plane of a spiral galaxy tends to significantly accelerate core collapse .

The different stages of core @-@ collapse may be divided into three phases . During a globular cluster 's adolescence , the process of core @-@ collapse begins with stars near the core . However , the interactions between binary star systems prevents further collapse as the cluster approaches middle age . Finally , the central binaries are either disrupted or ejected , resulting in a tighter concentration at the core .

The interaction of stars in the collapsed core region causes tight binary systems to form . As other stars interact with these tight binaries , they increase the energy at the core , which causes the cluster to re @-@ expand . As the mean time for a core collapse is typically less than the age of the galaxy , many of a galaxy 's globular clusters may have passed through a core collapse stage , then re @-@ expanded .

The Hubble Space Telescope has been used to provide convincing observational evidence of this stellar mass @-@ sorting process in globular clusters . Heavier stars slow down and crowd at the cluster 's core , while lighter stars pick up speed and tend to spend more time at the cluster 's periphery . The globular star cluster 47 Tucanae , which is made up of about 1 million stars , is one of the densest globular clusters in the Southern Hemisphere . This cluster was subjected to an intensive photographic survey , which allowed astronomers to track the motion of its stars . Precise velocities were obtained for nearly 15 @,@ 000 stars in this cluster .

A 2008 study by John Fregeau of 13 globular clusters in the Milky Way shows that three of them have an unusually large number of X @-@ ray sources , or X @-@ ray binaries , suggesting the clusters are middle @-@ aged . Previously , these globular clusters had been classified as being in old age because they had very tight concentrations of stars in their centers , another test of age

used by astronomers . The implication is that most globular clusters , including the other ten studied by Fregeau , are not in middle age as previously thought , but are actually in ' adolescence ' .

The overall luminosities of the globular clusters within the Milky Way and the Andromeda Galaxy can be modeled by means of a gaussian curve . This gaussian can be represented by means of an average magnitude Mv and a variance ?2 . This distribution of globular cluster luminosities is called the Globular Cluster Luminosity Function (GCLF) . (For the Milky Way , Mv
= ? 7 @.@ 20 ± 0 @.@ 13 , ? =
1 @.@ 1 ± 0 @.@ 1 magnitudes .) The GCLF has also been used as a " standard candle " for measuring the distance to other galaxies , under the assumption that the globular clusters in remote galaxies follow the same principles as they do in the Milky Way .

N @-@ body simulations

Computing the interactions between the stars within a globular cluster requires solving what is termed the N @-@ body problem . That is , each of the stars within the cluster continually interacts with the other N ? 1 stars , where N is the total number of stars in the cluster . The naive CPU computational " cost " for a dynamic simulation increases in proportion to N 2 (each of N objects must interact pairwise with each of the other N objects) , so the potential computing requirements to accurately simulate such a cluster can be enormous . An efficient method of mathematically simulating the N @-@ body dynamics of a globular cluster is done by subdividing into small volumes and velocity ranges , and using probabilities to describe the locations of the stars . The motions are then described by means of a formula called the Fokker ? Planck equation . This can be solved by a simplified form of the equation , or by running Monte Carlo simulations and using random values . However the simulation becomes more difficult when the effects of binaries and the interaction with external gravitation forces (such as from the Milky Way galaxy) must also be included .

The results of N @-@ body simulations have shown that the stars can follow unusual paths through the cluster , often forming loops and often falling more directly toward the core than would a single star orbiting a central mass . In addition , due to interactions with other stars that result in an increase in velocity , some of the stars gain sufficient energy to escape the cluster . Over long periods of time this will result in a dissipation of the cluster , a process termed evaporation . The typical time scale for the evaporation of a globular cluster is 1010 years . In 2010 it became possible to directly compute , star by star , N @-@ body simulations of a globular cluster over the course of its lifetime .

Binary stars form a significant portion of the total population of stellar systems , with up to half of all stars occurring in binary systems . Numerical simulations of globular clusters have demonstrated that binaries can hinder and even reverse the process of core collapse in globular clusters . When a star in a cluster has a gravitational encounter with a binary system , a possible result is that the binary becomes more tightly bound and kinetic energy is added to the solitary star . When the massive stars in the cluster are sped up by this process , it reduces the contraction at the core and limits core collapse .

The ultimate fate of a globular cluster must be either to accrete stars at its core , causing its steady contraction , or gradual shedding of stars from its outer layers .

Intermediate forms

The distinction between cluster types is not always clear @-@ cut , and objects have been found that blur the lines between the categories . For example , BH 176 in the southern part of the Milky Way has properties of both an open and a globular cluster .

In 2005 , astronomers discovered a completely new type of star cluster in the Andromeda Galaxy , which is , in several ways , very similar to globular clusters . The new @-@ found clusters contain hundreds of thousands of stars , a similar number to that found in globular clusters . The clusters share other characteristics with globular clusters such as stellar populations and metallicity . What distinguishes them from the globular clusters is that they are much larger ? several hundred light

@-@ years across ? and hundreds of times less dense . The distances between the stars are , therefore , much greater within the newly discovered extended clusters . Parametrically , these clusters lie somewhere between a globular cluster and a dwarf spheroidal galaxy .

How these clusters are formed is not yet known , but their formation might well be related to that of globular clusters . Why M31 has such clusters , while the Milky Way does not , is not yet known . It is also unknown if any other galaxy contains these types of clusters , but it would be very unlikely that M31 is the sole galaxy with extended clusters .

= = Tidal encounters = =

When a globular cluster has a close encounter with a large mass , such as the core region of a galaxy , it undergoes a tidal interaction . The difference in the pull of gravity between the part of the cluster nearest the mass and the pull on the furthest part of the cluster results in a tidal force . A " tidal shock " occurs whenever the orbit of a cluster takes it through the plane of a galaxy .

As a result of a tidal shock , streams of stars can be pulled away from the cluster halo , leaving only the core part of the cluster . These tidal interaction effects create tails of stars that can extend up to several degrees of arc away from the cluster . These tails typically both precede and follow the cluster along its orbit . The tails can accumulate significant portions of the original mass of the cluster , and can form clumplike features .

The globular cluster Palomar 5 , for example , is near the apogalactic point of its orbit after passing through the Milky Way . Streams of stars extend outward toward the front and rear of the orbital path of this cluster , stretching out to distances of 13 @,@ 000 light @-@ years . Tidal interactions have stripped away much of the mass from Palomar 5 , and further interactions as it passes through the galactic core are expected to transform it into a long stream of stars orbiting the Milky Way halo .

Tidal interactions add kinetic energy into a globular cluster , dramatically increasing the evaporation rate and shrinking the size of the cluster . Not only does tidal shock strip off the outer stars from a globular cluster , but the increased evaporation accelerates the process of core collapse . The same physical mechanism may be at work in dwarf spheroidal galaxies such as the Sagittarius Dwarf , which appears to be undergoing tidal disruption due to its proximity to the Milky Way .

= = Orbits = =

There are many globular clusters with a retrograde orbit round the Milky Way Galaxy . A hypervelocity globular cluster was discovered around Messier 87 in 2014 , having a velocity in excess of the escape velocity of M87 .

= = Planets = =

Astronomers are searching for exoplanets of stars in globular star clusters .

In 2000 , the results of a search for giant planets in the globular cluster 47 Tucanae were announced . The lack of any successful discoveries suggests that the abundance of elements (other than hydrogen or helium) necessary to build these planets may need to be at least 40 % of the abundance in the Sun . Terrestrial planets are built from heavier elements such as silicon , iron and magnesium . The very low abundance of these elements in globular clusters means that the member stars have a far lower likelihood of hosting Earth @-@ mass planets , when compared to stars in the neighborhood of the Sun . Hence the halo region of the Milky Way galaxy , including globular cluster members , are unlikely to host habitable terrestrial planets .

In spite of the lower likelihood of giant planet formation , just such an object has been found in the globular cluster Messier 4 . This planet was detected orbiting a pulsar in the binary star system PSR B1620 @-@ 26 . The eccentric and highly inclined orbit of the planet suggests it may have been formed around another star in the cluster , then was later " exchanged " into its current arrangement . The likelihood of close encounters between stars in a globular cluster can disrupt planetary systems , some of which break loose to become free floating planets . Even close orbiting planets

can become disrupted , potentially leading to orbital decay and an increase in orbital eccentricity and tidal effects .

General resources

 NASA Astrophysics Data System has a collection of past articles , from all major astrophysics journals and many conference proceedings .
 SCYON is a newsletter dedicated to star clusters .
 MODEST is a loose collaboration of scientists working on star clusters .

Books

 Binney , James ; Tremaine , Scott (1987) . Galactic Dynamics (First ed .) . Princeton , New Jersey : Princeton University Press . ISBN 0 @-@ 691 @-@ 08444 @-@ 0 .
 Heggie , Douglas ; Hut , Piet (2003) . The Gravitational Million @-@ Body Problem : A Multidisciplinary Approach to Star Cluster Dynamics . Cambridge University Press . ISBN 0 @-@ 521 @-@ 77486 @-@ 1 .
 Spitzer , Lyman (1987) . Dynamical Evolution of Globular Clusters . Princeton , New Jersey : Princeton University Press . ISBN 0 @-@ 691 @-@ 08460 @-@ 2 .

Review articles

 Elson , Rebecca ; Hut , Piet ; Inagaki , Shogo (1987) . Dynamical evolution of globular clusters . Annual review of astronomy and astrophysics 25 565 . Bibcode : 1987ARA & A .. 25 .. 565E
 Meylan , G. ; Heggie , D. C. (1997) . Internal dynamics of globular clusters . The Astronomy and Astrophysics Review 8 1 . Bibcode : 1997A & ARv ... 8 .... 1M