Star clusters

Star clusters are groups of stars which are gravitationally bound. Two distinct types of star cluster can be distinguished: ***globular clusters*** are tight groups of hundreds of thousands of very old stars, while ***open clusters*** generally contain less than a few hundred members, and are often very young. Open clusters become disrupted over time by the gravitational influence of giant molecular clouds as they move through the galaxy, but cluster members will continue to move in broadly the same direction through space even though they are no longer gravitationally bound; they are then known as a stellar association, sometimes also referred to as a ***moving group***.

The study of star clusters is very important in many areas of astronomy. Because the stars were all born at roughly the same time, the different properties of all the stars in a cluster are a function only of mass, and so stellar evolution theories rely on observations of open and globular clusters. Clusters are also a crucial step in determining the distance scale of the universe. A few of the nearest clusters are close enough for their distances to be measured using parallax. A Hertzsprung-Russell diagram can be plotted for these clusters which has absolute values known on the luminosity axis. Then, when similar diagram is plotted for a cluster whose distance is not known, the position of the main sequence can be compared to that of the first cluster and the distance estimated. This process is known as main-sequence fitting. Reddening and stellar populations must be accounted for when using this method.

In 2005, astronomers discovered a completely new type of star cluster (***extended globular clusters***) in Andromeda Galaxy, which are, in several ways, very similar to globular clusters (although less dense). These new-found star clusters contain hundreds of thousands of stars, a similar number of stars that can be found in globular clusters. The clusters also share other characteristics with globular clusters, *e.g.* the 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 (low dark-matter) globular cluster and a (dark matter-dominated) 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 has not, is not yet known. It is also unknown if any other galaxy contains this kind of clusters, but it would be very unlikely that M31 is the sole galaxy with extended clusters.

Open clusters

An **open cluster** (***galactic cluster***) is a group of up to a few thousand stars that were formed from the same giant molecular cloud, and are still loosely gravitationally bound to each other.

- In contrast, globular clusters are very tightly bound by gravity. Open clusters are found only in spiral and irregular galaxies, in which active star formation is occurring.
- They are usually less than a few hundred million years old: they become disrupted by close encounters with other clusters and clouds of gas as they orbit the galactic center, as well as losing cluster members through internal close encounters.
- Young open clusters may still be contained within the molecular cloud from which they formed, illuminating it to create an H II region. Over time, radiation pressure from the cluster will disperse the molecular cloud. Typically, about 10% of the mass of a gas cloud will coalesce into stars before radiation pressure drives the rest away.
- Open clusters are very important objects in the study of stellar evolution. Because the stars are all of very similar age and chemical composition, the effects of other more subtle variables on the properties of stars are much more easily studied than they are for isolated stars.

Formation

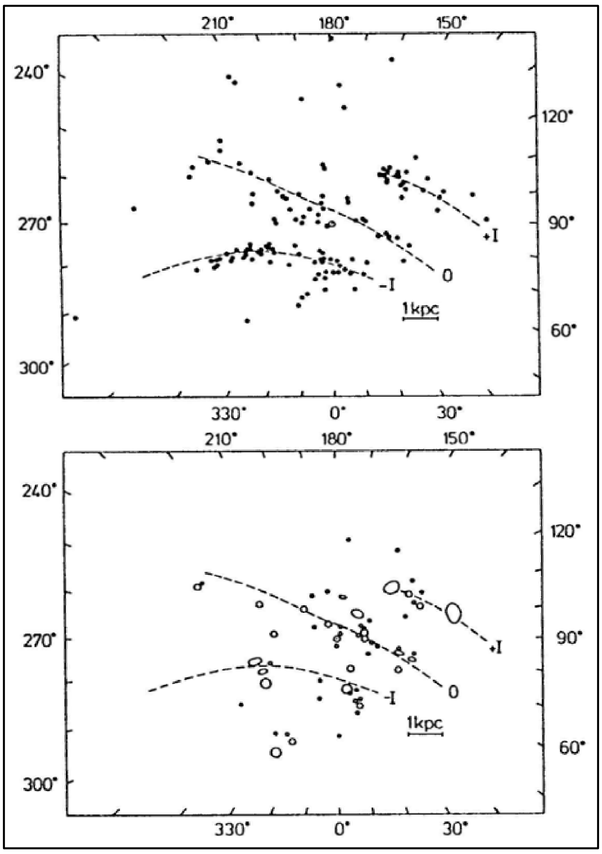
- A large fraction of stars are originally formed in multiple systems because only a cloud of gas containing many times the mass of the Sun will be heavy enough to collapse under its own gravity, but such a heavy cloud cannot collapse into a single star.
- The formation of an open cluster begins with the collapse of part of a giant molecular cloud, a cold dense cloud of gas containing up to many thousands of times the mass of the Sun. Many factors may trigger the collapse of a giant molecular cloud (or part of it) and a burst of star formation which will result in an open cluster, including shock waves from a nearby supernova and gravitational interactions. Once a giant molecular cloud begins to collapse, star formation proceeds via successive fragmentations of the cloud into smaller and smaller clumps, resulting eventually in the formation of up to several thousand stars.
- In our own galaxy, the formation rate of open clusters is estimated to be one every few thousand years.
- Once star formation has begun, the hottest and most massive stars (known as OB stars) will emit copious amounts of ultraviolet radiation. This radiation rapidly ionizes the surrounding gas of the giant molecular cloud, forming an H II region. Stellar winds from the massive stars and radiation pressure begin to drive away the gases; after a few million years the cluster will experience its first supernovae, which will also expel gas from the system.
- After a few tens of millions of years, the cluster will be stripped of gas and no further star formation will take place. Typically, less than 10% of the gas originally in the cluster will form into stars before it is dissipated.
- Another view to cluster formation is that they form rapidly out of a contracting molecular cloud core and once the massive stars begin to shine they expel the residual gas with the sound speed of the hot ionized gas. From the time of start of cloud-core contraction to gas expulsion takes typically not more than one to three million years. As only 30 to 40 per cent of the gas in the cloud core forms stars, the process of residual gas expulsion is highly damaging to the cluster which loses many and perhaps all of its stars.
- It is common for two or more separate open clusters to form out of the same molecular cloud. In the Large Magellanic Cloud, both Hodge 301 and R136 are forming from the gases of the Tarantula Nebula, while in our own galaxy, tracing back the motion through space of the Hyades and Praesepe, two prominent nearby open clusters, suggests that they formed in the same cloud about 600 million years ago. Sometimes, two clusters born at the same time will form ***a binary cluster***. The best known example in the Milky Way is the Double Cluster of h Persei and χ Persei, but at least 10 more double clusters are known to exist.

Mrphology and classification

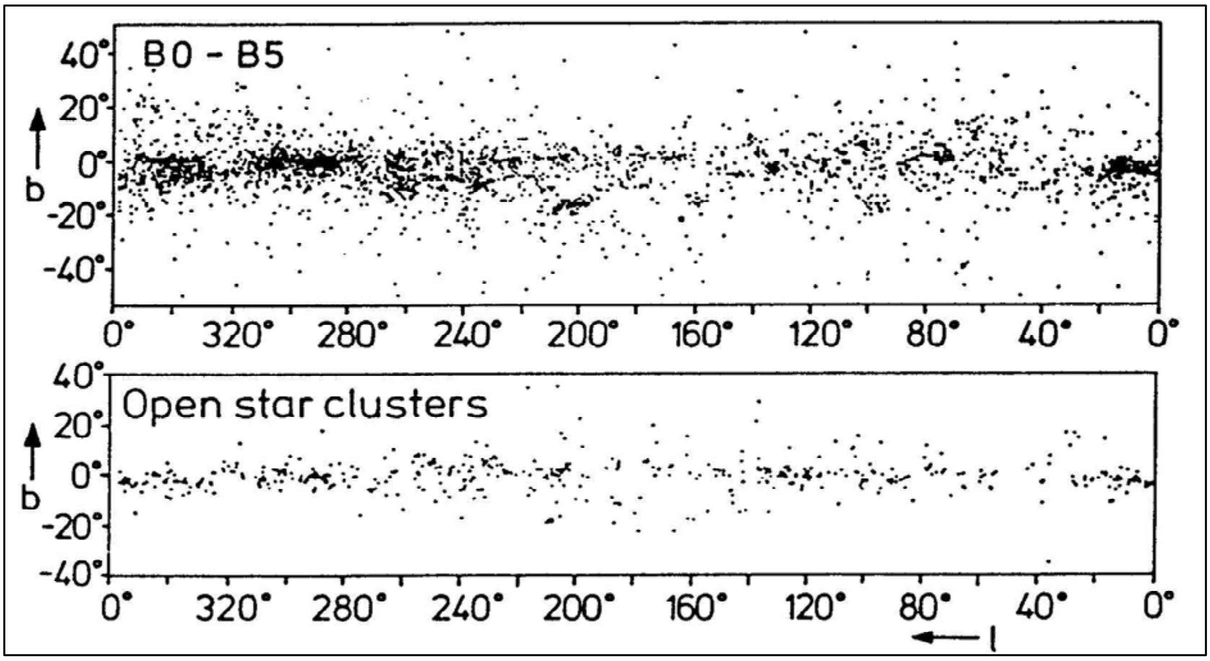
- Open clusters range from very sparse clusters with only a few members to large concentrations containing thousands of stars. They usually consist of quite a distinct dense core, surrounded by a more diffuse 'corona' of cluster members. The core is typically about 3–4 light years across, with the corona extending to about 20 light years from the cluster centre. Typical star densities in the centre of a cluster are about 1.5 stars per cubic light year.
- Open clusters are often classified according to a scheme developed by Robert Trumpler in 1930. The Trumpler scheme gives a cluster a three part designation, with a Roman numeral from I-IV indicating its concentration and detachment from the surrounding star field (from strongly to weakly concentrated), an Arabic numeral from 1 to 3 indicating the range in brightness of members (from small to large range), and *p*, *m* or *r* to indication whether the cluster is poor, medium or rich in stars. An, 'n' is appended if the cluster lies within nebulosity.
- Under the Trumpler scheme, the Pleiades are classified as I3rn (strongly concentrated and richly populated with nebulosity present), while the nearby Hyades are classified as II3m (more dispersed, and with fewer members).

Numbers and distribution

- There are over 1,000 known open clusters in our galaxy, but the true total may be up to ten times higher than that.
- In spiral galaxies, open clusters are invariably found in the spiral arms where gas densities are highest and so most star formation occurs, and clusters usually disperse before they have had time to travel beyond their spiral arm. Open clusters are strongly concentrated close to the galactic plane, with a scale height in our galaxy of about 180 light years.
- In irregular galaxies, open clusters may be found throughout the galaxy, although their concentration is highest where the gas density is highest.



Young open clusters and OB associations in the galactic plane are found mainly in the spiral arms.



The galactic distributions of both early B-type field stars and open clusters closely follow the Milky Way and are only found close to the galactic. For open clusters, the galactic latitude is $b \leq 5^{\circ}$ in most cases and very few >10°.

- Open clusters are not seen in elliptical galaxies: star formation ceased many millions of years ago in elliptical galaxies, and so the open clusters which were originally present have long since dispersed.
- In our galaxy, the distribution of clusters depends on age, with older clusters being preferentially found at greater distances from the galactic centre. Tidal forces are stronger nearer the centre of the galaxy, increasing the rate of disruption of clusters, and also the giant molecular clouds which cause the disruption of clusters are concentrated towards the inner regions of the galaxy, so clusters in the inner regions of the galaxy tend to get dispersed at a younger age than their counterparts in the outer regions.

<u>**Stellar composition**</u>

- Because open clusters tend to be dispersed before most of their stars reach the end of their lives, the light from them tends to be dominated by the young, hot blue stars. These stars are the most massive, and have the shortest lives of a few tens of millions of years. The older open clusters tend to contain more yellow stars.
- Some open clusters contain hot blue stars which seem to be much younger than the rest of the cluster. These blue stragglers are also observed in globular clusters, and in the very dense cores of globular clusters they are believed to originate when stars collide, forming a much hotter and more

massive star. It is thought that most of them probably originate when dynamical interactions with other stars cause a binary system to coalesce into one star.

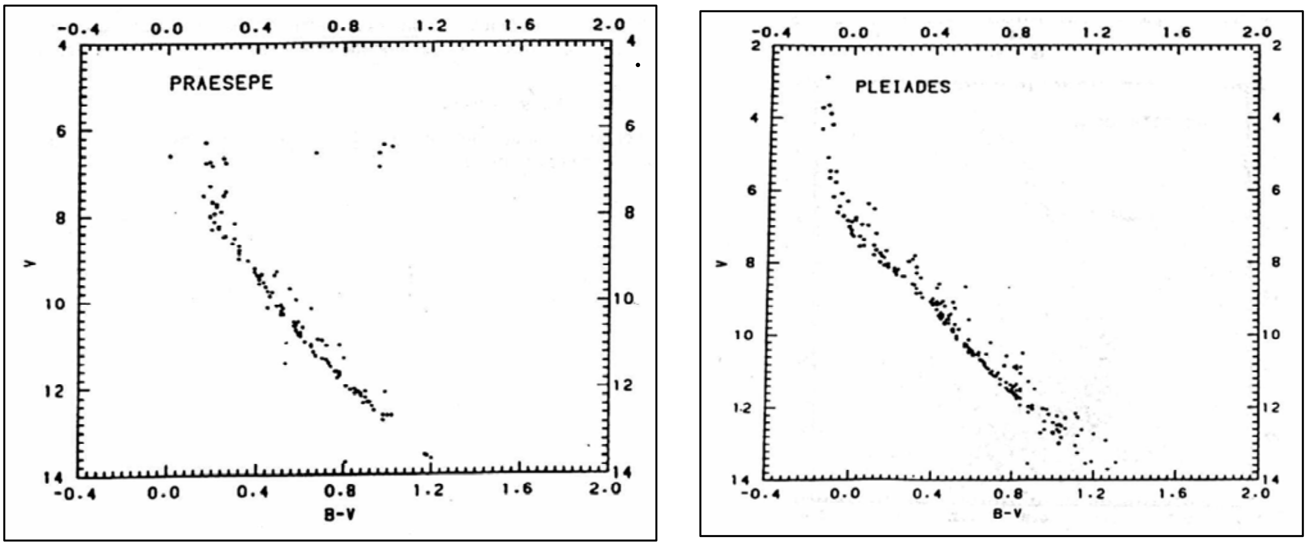
- Once they have exhausted their supply of hydrogen through nuclear fusion, medium to low mass stars shed their outer layers to form a planetary nebula and evolve into white dwarfs.
- While most clusters become dispersed before a large proportion of their members have reached the white dwarf stage, the number of white dwarfs in open clusters is still generally much lower than would be expected, given the age of the cluster and the expected initial mass distribution of the stars. One possible explanation for the lack of white dwarfs is that when a red giant expels its outer layers to become a planetary nebula, a slight asymmetry in the loss of material could give the star a 'kick' of a few kilometers per second, enough to eject it from the cluster.

Eventual fate

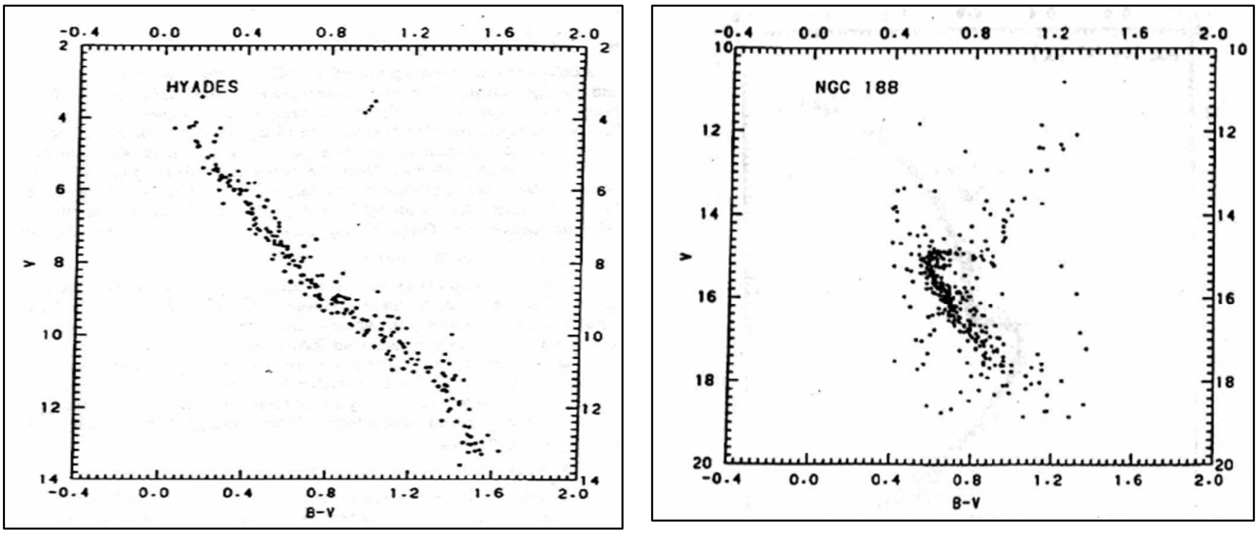
- Many open clusters are inherently unstable, with a small enough mass that the escape velocity of the system is lower than the average velocity of the constituent stars. These clusters will rapidly disperse within a few million years.
- Clusters which have enough mass to be gravitationally bound once the surrounding nebula has evaporated can remain distinct for many tens of millions of years, but over time internal and external processes tend also to disperse them.
- Internally, close encounters between members of the cluster will often result in the velocity of one being increased to beyond the escape velocity of the cluster, which results in the gradual 'evaporation' of cluster members.
- Externally, about every half-billion years or so an open cluster tends to be disturbed by external factors such as passing close to or through a molecular cloud. The gravitational tidal forces generated by such an encounter tend to disrupt the cluster.
- Eventually, the cluster becomes a stream of stars, not close enough to be a cluster but all related and moving in similar directions at similar speeds.
- The timescale over which a cluster disrupts depends on its initial stellar density, with more tightly packed clusters persisting for longer. Estimated cluster half lives, after which half the original cluster members will have been lost, range from 150–800 million years, depending on the original density.
- After a cluster has become gravitationally unbound, many of its constituent stars will still be moving through space on similar trajectories, in what is known as a **stellar association**, ***moving cluster*** or ***moving group***.

Studying stellar evolution

- Because the stars in an open cluster are all at roughly the same distance from Earth, and were born at roughly the same time from the same raw material, the differences in apparent brightness among cluster members is due only to their mass. This makes open clusters very useful in the study of stellar evolution, because when comparing one star to another, many of the variable parameters are fixed.
- When a Hertzsprung-Russell (H-R) diagram is plotted for an open cluster, most stars lie on the ***main sequence***. The most massive stars have begun to evolve away from the main sequence and are becoming ***red giants***; the position of the ***turn-off*** from the main sequence can be used to estimate the age of the cluster.



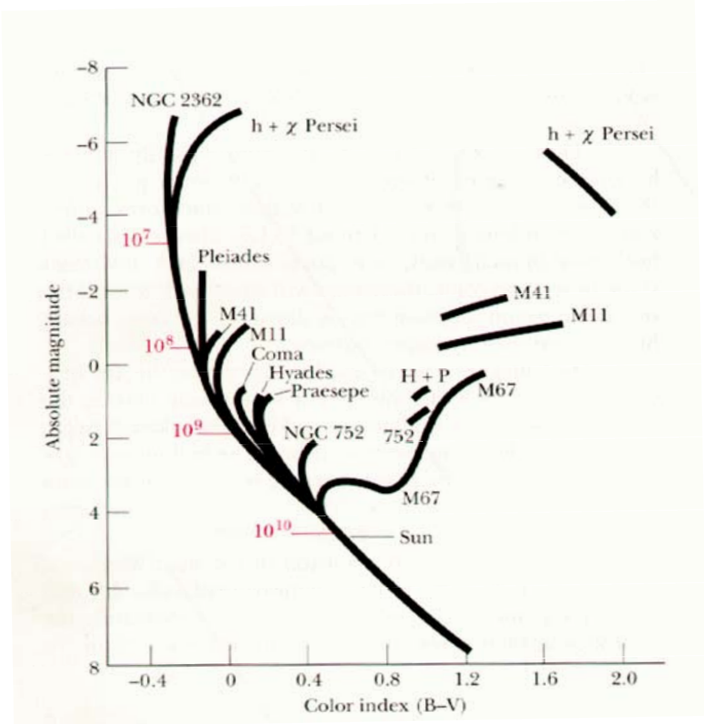
Color-magnitude diagrams for Pleiades and Praesepe open clusters



Color-magnitude diagrams for Hyades and NGC 188 open clusters.

- By studying the HR diagram for a cluster, we are studying a group of stars with a common distance. We can study their relative properties without knowing what their actual distance is.
- If we know the distance to the cluster, we plot directly the absolute magnitudes on the H-R diagram. If we don't know the distance, we plot the apparent magnitudes. We then see how many magnitudes we have to shift the diagram up or down to calculate the right absolute magnitudes for each spectral type. The amount of shift gives the distance modulus for the cluster, and therefore the distance (using distance modulus relation). This procedure is known as ***main sequence fitting***.

- The H-R diagram for a group of clusters as shown in the figure. Note that the lower (cooler or later) part of the main sequence is the same for all the clusters shown. The hotter stars all appear to be above the main sequence. The point at which this happens for a given cluster is called the turn-off point. Stars of earlier spectral type (hooter than) the turn-off point appear above the main sequence, meaning that they are more luminous, and therefore larger than main sequence stars of the same spectral type.



Composite HR diagram for open star clusters

- Each cluster has its turn-off point at a different spectral type. We interpret this behavior as representing stellar aging, in which stars use up their basic fuel supply. Hotter (more massive) stars evolve faster than cooler (low mass) stars, and leave the main sequence sooner. We assume that the stars in a cluster were formed approximately the same time. As cluster ages, later and later spectral types evolve away from the main sequence. This means the turn-off point shifts to later spectral types as the cluster ages. We can tell the relative age of two clusters by comparing their turn-off points. If we know how long different spectral type stars actually stay on the main sequence, we can tell the absolute age of a cluster from its turn-off point.
- We note that there are some galactic clusters that are missing the lower (cooler) end of the main sequence. We think that these clusters are very young. The lower mass stars are still in the process of collapse, and have not yet reached the main sequence.

- ***Features of the HR diagram for a galactic cluster:***

- Zero-age main sequence (ZAMS): The locus of stars which have just started to shine.

- Subgiants branch: Stars that have just exhausted H in their cores, and are now moving off the main sequence.

- Red giants: Evolved stars in upper right-hand part of diagram with either He cores, or they are burning He to C and O in their cores. They have H-burning shell. These were once the more massive MS stars.`

Distances of some well-known clusters

Cluster	distance				
Hyades	44 pc	Pleiades	127 pc	Praesepe	159 pc
Sco-Cen	170 pc	M67	830 pc	h Persei	2250 pc
χ Persei	2400 pc				

Open clusters and the astronomical distance scale

- Determining the distances to astronomical objects is crucial to understanding them, but the vast majority of objects are too far away for their distances to be directly determined.
- Calibration of the astronomical distance scale relies on a sequence of indirect and sometimes uncertain measurements relating the closest objects, for which distances can be directly measured, to increasingly distant objects. Open clusters are a crucial step in this sequence.
- The closest open clusters can have their distance measured directly by one of two methods. First, the parallax method. Clusters such as the Pleiades, Hyades, within about 500 light years, are close enough for this method to be viable (the results from the Hipparcos position-measuring satellite yielded accurate distances for several clusters). The other direct method is the so-called moving cluster method. The Hyades are the best known application of this method, which reveals their distance to be 46.3 parsecs.
- Once the distances to nearby clusters have been established, further techniques can extend the distance scale to more distant clusters. By matching the main sequence on the H-R diagram for a cluster at a known distance with that of a more distant cluster, the distance to the more distant cluster can be estimated.
- Accurate knowledge of open cluster distances is vital for calibrating the period-luminosity relationship shown by variable stars such as cepheid and RR Lyrae stars, which allows them to be used as standard candles. These luminous stars can be detected at great distances, and are then used to extend the distance scale to nearby galaxies in the Local Group.

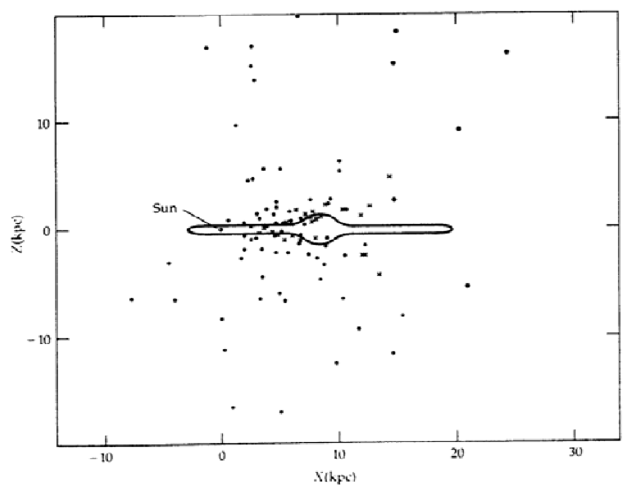
Globular clusters

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 (open) clusters, which are found in the disk.
- Globular clusters are fairly common; there are about 150 currently known globular clusters in the Milky Way, with perhaps 10–20 more undiscovered. Large galaxies can have more: Andromeda, may have as many as 500. Some giant elliptical galaxies, such as M87, may have as many as 10,000 globular clusters.
- These globular clusters orbit the galaxy out to large radii, 40 kpc (approximately 131 thousand light years) or more.
- 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 and Canis Major Dwarf galaxies 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 were 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.
- A total of 151 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 examined the cepheid variables in the clusters and would use their period–luminosity relationship for distance estimates.
- Of the globular clusters within our Milky Way, the majorities are found in the vicinity of the galactic core, and the large majorities 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 significantly in error, it did demonstrate that the dimensions of the galaxy were much greater than had been previously thought. His error was due to the fact that 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 of 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.
- 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.)

Composition

- Globular clusters are generally composed of hundreds of thousands of low-metal, old stars. The 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 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.
- While 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), 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 due to 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 10^8 years. However, there has been at least one planetary system found orbiting a pulsar (PSR B1620−26) that belongs to the globular cluster M4.
- With a few notable exceptions, each globular cluster appears to have a definite age. That is, most of the stars in a cluster are at approximately the same stage in stellar evolution, suggesting that they formed at about the same time.
- All known globular clusters appear to have no 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.
- Some globular clusters, like Omega Centauri in our Milky Way and G1 in M31, are extraordinarily massive (several million solar masses) and contain multiple stellar populations. Both can be regarded as evidence that super-massive globular clusters are in fact the cores of dwarf galaxies that are consumed by the larger galaxies.
- 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 metallic content compared to Population I stars such as the Sun. (To astronomers, ***metals*** includes all elements heavier than helium, such as lithium and carbon.)

- The Dutch astronomer Pieter Oosterhoff noticed that there appear to be two populations of globular clusters, which became known as ***Oosterhoff groups***. These two populations have been observed in many galaxies (especially massive elliptical galaxies). Both groups are of similar ages (nearly as old as the universe itself) but differ in their metal abundances. 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" while type II are "metal-poor". 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 our Milky Way, *the metal-poor clusters are associated with the halo and the metal-rich clusters with the Bulge. 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.

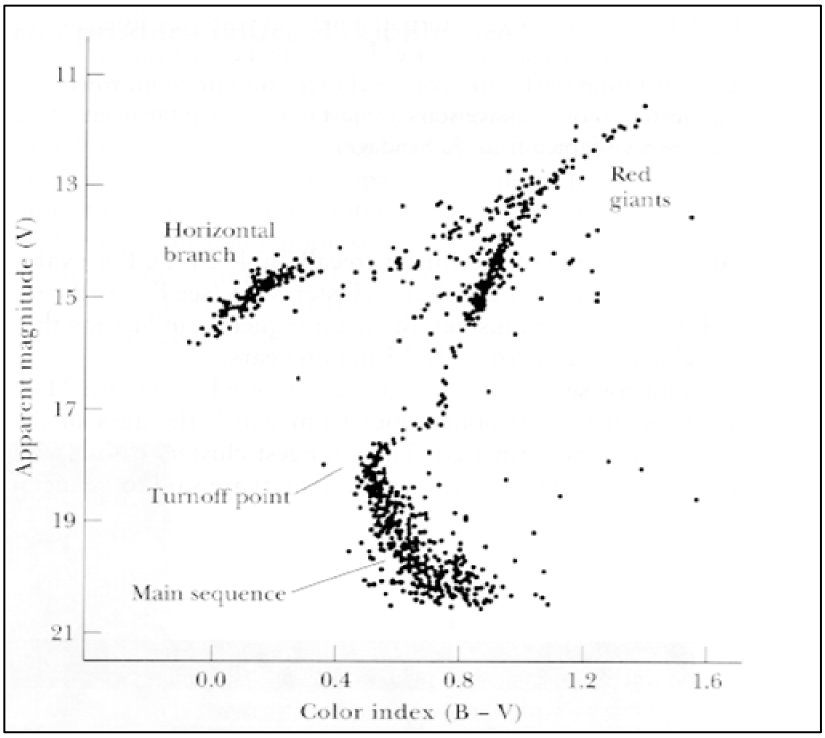
Exotic components

- 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.
- Astronomers have searched for black holes within globular clusters since the 1970s. In independent programs, a 4,000 solar mass intermediate-mass black hole has been suggested to exist based on HST observations in the globular cluster M15 and a 20,000 solar mass 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 super-massive black holes discovered at the cores of galaxies. Claims of intermediate mass black holes have been met with some skepticism. The densest objects in globular clusters are expected to migrate to the

cluster center due to mass segregation. These will be white dwarfs and neutron stars in an old stellar population like a globular cluster.

Color-magnitude diagram

- The H-R 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.



- The H-R diagrams for globular clusters appear to be different from that of galactic clusters. For globular clusters, only the lower (cooler) part of the main sequence is present. All earlier spectral types have turned off the main sequence. This tells us that globular clusters must be very old. Globular clusters contain a large number of red giants.
- 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, 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 collected stars. The most massive main sequence stars in a globular cluster 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 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. During the early 1990s, 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 COBE have resolved this issue as have computer models of stellar evolution that have different models of mixing.
- 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 change in the evolutionary tracks due to the abundance of heavy elements. (Heavy elements in astronomy are considered to be all elements more massive than helium.) The data obtained from studies of globular clusters are then used to study the evolution of the Milky Way as a whole.

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. (A possible exception is when strong tidal interactions with other large masses result in the dispersal of the stars.)
- At present the formation of globular clusters remains a poorly understood phenomenon. 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. This star-forming period is relatively brief, however, compared to the age of many globular clusters. 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.

- After they are formed, the stars in the globular cluster begin to gravitationally interact 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 10^9 years.

Ellipticity of Globulars

Galaxy	**Ellipticity**
Milky Way	0.07±0.04
LMC	0.16±0.05
SMC	0.19±0.06
M31	0.09±0.04

- 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.

Mass segregation and luminosity

- In measuring the luminosity curve of a given globular cluster as a function of distance from the core, most clusters in the Milky Way steadily increase 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 steadily increase 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 encounter their less massive companions. As a result of the encounters the larger stars tend to lose kinetic energy and start to settle toward the core. Over a lengthy period of time this leads to a concentration of massive stars near the core, a phenomenon called mass segregation.
- 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.
- The overall luminosities of the globular clusters within the Milky Way and M31 can be modeled by means of a gaussian curve. This gaussian can be represented by means of an average magnitude M_v and a variance σ^2. This distribution of globular cluster luminosities is called the Globular Cluster Luminosity Function (GCLF). (For the Milky Way, M_v = −7.20±0.13, σ=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.

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 clump-like features.
- The globular cluster Palomar 5, for example, is near the perigalactic 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.

Stellar association

A **stellar association**, or **moving group**, is a very loose star cluster, looser than both open clusters and globular clusters. Stellar associations will normally contain from 10 to 100 or more stars. The stars share a common origin, but have become gravitationally unbound and are still moving together through space. Moving groups are primarily identified by their common movement vectors and ages. The conventional name for an association uses the names or abbreviations of the constellation (or constellations) in which they are located; the association type, and, sometimes, a numerical identifier. Stellar associations were first discovered by the Armenian astronomer Viktor Ambartsumian in 1947. He categorized them into two groups, OB and T, based on the properties of their stars.

OB associations

- Young associations will contain 10–100 massive stars of spectral class O and B, and are known as **OB associations**. These are believed to form within the same small volume inside a giant molecular cloud. Once the surrounding dust and gas is blown away, the remaining stars become unbound and begin to drift apart. It is believed that the majority of all stars in the Milky Way were formed in OB associations.
- O class stars are short-lived, and will expire as supernovae after roughly a million years. As a result, OB associations are generally only a few million years in age or less. The O-B stars in the association will have burned all their fuel within 10 million years. (Compare this to the current age of the Sun at about 5 billion years.)
- The Hipparcos satellite provided measurements that located a dozen OB associations within 650 parsecs of the Sun. The nearest OB association is the Scorpius-Centaurus Association, located about 400 light years from the Sun.
- OB associations have also been found in the Large Magellanic Cloud and the Andromeda Galaxy. These associations can be quite sparse, spanning 1,500 light years in diameter.

T associations

- Young stellar groups can contain a number of infant T Tauri stars that are still in the process of entering the main sequence. These sparse populations of up to a thousand T Tauri stars are known as **T associations**. The nearest example is the Taurus-Auriga T association (Tau-Aur T association), located at a distance of 140 parsecs from the Sun. T associations are often found in the vicinity of the molecular cloud from which they formed. Some, but not all, include O-B class stars.

- To summarize the characteristics of Moving groups members: they have the same age and origin, the same chemical composition and they have the same amplitude and direction in their vector of velocity.

R associations

- Associations of stars that illuminate a reflection nebula are called **R associations**, a name suggested by Sidney van den Bergh after he discovered that the stars in these nebulae had a non-uniform distribution. These young stellar groupings contain main-sequence stars that are not sufficiently massive to disperse the interstellar clouds in which they formed. This allows the properties of the surrounding dark cloud to be examined by astronomers.
- Because R-associations are more plentiful than OB associations, they can be used to trace out the structure of the galactic spiral arms. An example of an R-association is Monoceros R2, located 830 ± 50 parsecs from the Sun.

Clusters as dynamical entities

In this part we look at the internal dynamics of star clusters. If the gravitational forces between the stars sufficient to keep the cluster together, we say the cluster is gravitational bound. As stars move around within the cluster, pairs of stars will pass near each other. The gravitational attraction between the two stars in the pair will alter the motion of each star. The momentum and energy of each star will change in this gravitational encounter. Thus, these encounters alter the distribution of speeds, the number of stars traveling at a given speed. If there has been sufficient time for many encounters to occur, the distribution of speeds will reach some equilibrium. When a cluster has reached this stage, we say that it is dynamically relaxed. *We refer to gravitational encounters as collisions even though the stars never actually get close enough for their surfaces to touch*.

The Virial theorem

In a dynamically relaxed system, the kinetic and potential energies are related in a very specific way. This relationship is known as the virial theorem. The viral theorem states that, for stable, self gravitating spherical distribution of equal mass objects (stars, cluster, galaxies, etc), the total kinetic energy (*K*) of the objects is equal to (– ½) times the total gravitational potential energy (*U*). The virial theorem applies to any gravitationally bound system that has had sufficient time to come to equilibrium. Even simple systems, like binary stars, obey the virial theorem. If the orbits are circular then $K = -\frac{U}{2}$ at all points. For elliptical orbits, r and v are changing, so *K* and *U* are changing, while their sum E is fixed. This means that we have to average over whole orbit to get $\langle K \rangle = -\frac{\langle U \rangle}{2}$.

Remember, for any system, the total energy is $E = K + U$, so $E = \frac{\langle U \rangle}{2}$.

Energies

We now look at the kinetic and potential energies of a cluster. We saw that the gravitational potential energy for a constant density sphere of mass *M* and radius *R* is

$$\langle U \rangle = -(3/5)\,GM^2/R. \qquad (1)$$

We now look at the kinetic energy. In cluster of stars, the kinetic energy is in the random motions of the stars. If the cluster has N stars each of mass m, the kinetic energy is

$$K = 1/2\,N\,m\,v^2. \qquad (2)$$

The overall system has a mass $M = N\,m$, then

$$K = (1/2)\,M\,v^2. \qquad (3)$$

If we put this and the potential energy into the virial theorem, we find

$$1/2M\ v^2 = -(1/2)\,\mathrm{x} - (3/5)\,GM^2/R \qquad \rightarrow \qquad M\left\langle v^2 \right\rangle = (3/5)\,GM^2/R \qquad (4)$$

Dividing both sides by *M* gives

$$\left\langle v^2 \right\rangle = (3/5)\,GM/R \qquad (5)$$

The quantity $\left\langle v^2 \right\rangle$ is the mean (average) of the square of the velocity. If we take the square root of this quantity, we have the root mean square velocity or ***rms*** velocity. It is a measure of the internal motions in the cluster.

Escape velocity

We can relate the gravitational potential energy to the escape velocity v_e, the speed with an object must be launched from the surface to escape permanently from the cluster. Consider a particle of mass m, moving outward from the surface at speed v_e. If the object escapes, it must getso far away that the potential energy is essentially zero. Since the kinetic energy is always greater than or equal to zero, the total energy of the far away must be greater than or equal to zero. Since the total energy is conserved, the total energy for an escaping object must be zero or positive when it is launched. The kinetic energy of the particle is

$$KE = (1/2)mv_e^2 \qquad (6)$$

Since it is at the surface of the sphere of mass *M* and radius *R*, its potential energy is just

$$PE = -GmM/R \qquad (7)$$

For the total energy to be zero (the condition that particle barely escapes), $KE = -PE$, giving

$$v_e^2 = 2GM/R \qquad (8)$$

Note that the escape velocity is approximately twice the ***rms*** speed. For a gravitationally bound system, we would expect $v_e > v_{rms}$. If there many particles have speeds greater than the escape velocity, the cluster would not be gravitationally bound.

Relaxation time

In a cluster, there wil be some stars with speeds greater than escape velocity. They will escape. This alter the velocity distribution by removing the highest velocity stars. . The remaining stars must adjust, re-establishing the equilibrium velocity distribution. We call the time it takes the system to re-establish equilibrium the relaxation time, t_{rel}. We can estimate the relaxation time by following a single star as it moves through the cluster. We assume that are n stars per unit volume in the cluster. We would like to know how long our star will go between collisions with other stars. That depends, in part, on how we define a distance *r* and say that if two stars pass within this distance we will count it as a collision. We define r so that the PE of the star is equal in magnitude to the KE of our star. If our star is moving with speed v, this means that r is defined by

$$Gm^2 / r = mv^2 / r \qquad (9)$$

We can think of our star as sweeping out in a cylinder in a given time t_{rel}. The radius of the cylinder is r, and the length is $\pi r^2 v t_{rel}$. The number of stars in this volume is n multiplied by the volume. If we define t_{rel} do that it is the time for one collision, we have the condition

$$n(\pi r^2 v t_{rel}) = 1 \qquad (10)$$

Solving for t_{rel} gives

$$t_{rel} = 1/n\pi n^2 v \qquad (11)$$

Substituting for r from equation (9) gives

$$t_{rel} = v^3 / 4\pi G^2 m^2 n \qquad (12)$$

The number of stars per unit volume is simply

$$n = \frac{N}{(4\pi/3)R^3} = \frac{M/m}{(4\pi/3)R^3} \qquad (13)$$

Substituting into equation (12) gives

$$t_{rel} = \frac{v^3 R^3}{3G^2 mM} = \frac{(R/v) v^4 R^2 (M/m)}{3G^2 M^2} \qquad (14)$$

Using the virial theorem to eliminate two factors of v^2, and ignoring numerical factors that are close to unity (since this is just an estimate), this simplifies to

$$t_{rel} \cong (R/v)(M/m) = NR/v \qquad (15)$$

Equation (15) is just an estimate in which the effects of a few close encounters dominate. A more detailed calculation shows that the effect of many distant encounters is to reduce t_{rel} by a factor of 12ln(N/2).

Virial masses for clusters

For dynamically relaxed clusters, we can use the virial theorem to estimate the mass of the cluster. For a uniform cluster, with *N* stars, each of mass *m*, and the total mass of the cluster $M = Nm$, the cluster potential energy is

$$U = -(3/5) GM^2 / R \qquad (16)$$

where *R* is the radius of the cluster. The kinetic energy is

$$K = (1/2) M \langle v^2 \rangle \qquad (17)$$

Substituting these into the Virial theorem gives

$$M\left\langle v^{2}\right\rangle = 3GM^{2}/5R \tag{18}$$

Solving for *M*, we have

$$M = \left(\frac{5}{3}\right)\frac{\left\langle v^{2}\right\rangle R}{G} \tag{19}$$

Therefore, we can estimate the virial mass of a system if we can observe: The true overall extent of the system *R* and the mean square of the velocities of the individual objects that comprise the system.