Globular Clusters

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INTRODUCTION

Globular clusters were first recorded by Charles Messier (1730–1817) when he was cataloging hazy objects that could be confused with comets. At the time he did not attach any special significance to the objects in his catalog, but some years later the Herschels resolved some of the brighter globular clusters into stars and thus became the first people to discover their true nature. All in all, Messier's catalog listed 27 objects that were later discovered to be globular clusters [S1]. Today, there are 131 known globular clusters in the Milky Way [B1] (most of which were discovered before 1900) and it is estimated that there are no more than 100 remaining to be found.

Globular clusters are roughly spherical systems containing large numbers of stars (as many as 100,000 [B1]). They have linear diameters that range from 20 to more than 100 Parsecs and typical densities of 0.4 star per cubic Parsec with an average stellar separation on the order of light months [A1]. Globular clusters are more concentrated toward their centers where the stellar density can range anywhere from 100 to more than 10,000 stars per cubic Parsec [M1]. The system of globular clusters in the Milky Way is also roughly spherical, with its center (approximately) coinciding with the galactic center. Indeed, it was the asymmetric distribution of globular clusters about the Sun that gave astronomers (starting with Harlow Shapley in 1918) their first clue about the location of the galactic center.

The known Milky Way globular clusters exhibit a variety of interesting features. Most contain variable stars (in particular, RR Lyrae variables) and therefore good estimates of their distances can be obtained. Since they contain so many stars, useful information about stellar evolution can be determined from the analysis of globular cluster stars. The distribution of properties throughout the system of globular clusters can give valueable insights into the origin of our Galaxy and even the universe. The rest of this paper will examine these ideas in more detail and will also discuss theories on globular cluster evolution which show that open clusters, globular clusters and elliptical galaxies have much that is in common.

FEATURES OF THE MILKY WAY GLOBULAR CLUSTERS

In order to study the spheroidal component of the Milky Way, it is very helpful to look at globular clusters. Globular clusters are very noticeable collections of spheroidal component stars. The density of the system of globular clusters is likely representative of the density in the spheroidal component as a whole [M1] and insofar as this is true, the study of globular clusters provides a uniquely powerful tool for studying the structure of the spheroidal component.

General

As noted earlier, globular clusters are generally very nearly spherical. They typically have axial ratios of 0.9:1 to 1:1, although there are some systems which are elongated, with an axial ratio of only 0.6:1 (the elongation occurs in the outer regions of these systems)

[M1]. Globular cluster orbits about the galactic center are also roughly spherical, having an average eccentricity of 0.6 or a ratio of 4 to 3 between the major and minor orbital axes [B1].

Globular clusters show widely varying degrees of concentrations. For example, Peterson and King [P1] calculate central densities using central surface brightness data that range from 3.05 (for NGC 5053) to $3.31 \cdot 10^5$ (M80) $\mathrm{M}_\odot/\mathrm{Pc}^3$. Shapley and Sawyer have defined concentration classes I–XII (I representing the heaviest concentration) in such a way that nearly equal numbers of globular clusters are found in each class.

The integrated visual magnitude, M_V, of globular clusters ranges from -5 to -10, peaking at about -8.5 with a half width of ± 1 magnitude [M1]. The integrated globular cluster spectral type has been found to vary from A5 through G5 with most clusters falling in the fairly narrow range F8 through G5. Therefore, the intrinsic color index of a globular cluster can be predicted fairly well and this will allow the amount of interstellar reddening between the cluster and the Sun to be determined. In general, the brightest stars in a globular cluster are red giants of absolute magnitude around -3 [B1]. These stars are 3 magnitudes brighter than the brightest blue-white stars in the cluster.

Sandage has determined the luminosity function for one globular cluster (M3) and found that it has a shape similar to the solar neighborhood luminosity function, except that there is a large hump around zero absolute magnitude due a large number of cluster type variables [B1]. Thus, it is likely [I1] that a large fraction of the stars in a globular cluster are of fairly low mass ($\sim .2\mathrm{M}_\odot$) as is true near the Sun. The globular cluster mass to luminosity ratio (in solar units) is approximately 1, therefore a typical globular cluster will have a mass of $2 \cdot 10^5 \mathrm{M}_\odot$ [M1].

Although globular clusters consist of many stars, they contain very little free gas or dust. The processes of star formation have essentially ceased to operate in these systems. This phenomenon (and other indications to be discussed later) imply globular clusters are very old, with ages from 5 to 15 billion years [B1] which would make them the oldest luminous objects observable in the Galaxy. There are some exceptions, however, to the general lack of activity in globular clusters. M15 contains a planetary nebula [V1] and x-ray bursts (with a rough periodicity) have been observed in 7 globular clusters [B1]. Also, H_α radiation of gaseous origin has been reported for several globular clusters including 3 of which have exhibited x-ray bursts [B1].

Color-Magnitude Diagrams: Ages and Chemical Compositions

Color-magnitude diagrams have been made from the stars of individual globular clusters (for example, approximately 1100 stars have been measured in M3 and M92 [B1]). These diagrams have proved to be extremely helpful in providing information about the ages, distances, composition and evolution of globular clusters as well as yielding useful data about stellar evolution.

A typical globular cluster color-magnitude diagram consists of several characteristic features [M1]. The upper end of the main sequence terminates at a late spectral type (although there are occasionally a few blue stragglers) and is joined continuously at this point to a subgiant branch. The exact location of the main sequence turnoff point will give a good indication of the globular cluster's age (based on theoretical models of stellar evolution). The subgiant branch merges into the red-giant branch which extends upwards and to the right. At the top of the red-giant branch are located the brightest stars in the globular cluster. A well defined horizontal branch (of nearly constant magnitude) lies to the left of the red-giant branch. In the middle of the horizontal branch lies a strip of instability where stars are normally not found. However, in globular clusters this gap is often found to contain RR Lyrae variables (nearly 300 in M3 [B1]). Thus, the RR Lyrae variables have been established as representatives of an unstable phase of stellar evolution and since they are located in the horizontal branch, they will be of virtually constant (absolute) magnitude.

Some problems are encountered when making color-magnitude diagrams from the stars in globular clusters. First, all measurements must be corrected for interstellar reddening. Next, any star in a globular cluster will be measured against a significantly bright background and this must be carefully taken into account in order to perform accurate measurements. Generally, the edges of globular clusters can be studied with star counts or stellar photometry. However, the centers are usually too crowded for star counts and can be analyzed usually only by surface photometry. The state of the art is photoelectric photometry which can reach faint individual stars at the edges of clusters, accurately measure central surface brightnesses and even disentangle crowded and overlapping star images [K3]. It can be seen that the measured distribution of stars in globular clusters will be biased. Only bright stars can be measured near the center due to crowding while at the edges, there will primarily be faint stars (the numbers of bright stars are normally very small outside the central region [K3]). Hence, no single group of stars (bright or faint) can be observed all the way from the center to the edge of a globular cluster.

Despite all of the above difficulties, very interesting results have been determined from globular cluster color-magnitude diagrams. One of these concerns the ages of globular clusters. As was mentioned above, the age of a globular cluster is a function of where its main sequence turnoff occurs. A comparison is performed to the turnoff luminosity of a theoretical model which has the same chemical composition as the globular cluster. To do this, it is necessary to know the cluster's distance modulus (which can be determined in a variety of ways to be discussed below). The results can be divided into 3 regions [D1]. All globular clusters within 5 kPc of the galactic center have very nearly the same age. This is consistent with the hypothesis of a rapid collapse of the spheroidal component in the early history of our Galaxy and subsequent chemical enrichment among globular clusters near the galactic center (more on this later). Globular clusters between 6 and 12 kPc have ages between 10 and 15 billion years with an uncertainty of 2 billion years. The oldest of these globular clusters are the ones most deficient in metal abundance. Finally, globular clusters further than 12 kPc from the galactic center tend to look as old or perhaps younger (up to 4 billion years in extreme cases) as the nearby globular clusters. It should be noted that all of these age estimates are only as good as the assumptions underlying the theoretical models used to derive them and it is probably unrealistic to believe that any ages are known to within only 2 billion years [M1]. There has been a great deal of debate about the techniques used for dating globular clusters, so any results such as the above are quite tentative.

Now, it is very important that a globular cluster's chemical composition be known fairly precisely in order to make an accurate age determination. For example, the turnoff luminosity is a sensitive function of helium abundance (however, this effect will tend to be balanced by an opposing shift in the location of the main sequence also due to the helium). For the oldest globular clusters, a value of 20% (25% ± 3% [M1]) for the helium concentration seems to make the best fit to the available data but because of uncertainties in the data, values between 20% and 30% also appear consistent [D1]. This value sets an upper limit on the amount of helium that was produced during the early stages of the universe (and has had a far reaching impact on speculations about the mechanism of the Big Bang).

A second important chemical composition parameter is metal abundance, [Fe/H]. This parameter can be determined by several methods, which include looking at ultraviolet excesses for cluster main sequence stars, measuring ΔS for cluster RR Lyrae variables and calibrating the brightest stars in a globular cluster against nearer stars of similar spectral type whose abundances can be determined spectroscopically. It is difficult, however, to examine spectra of individual stars in a globular cluster due to the stellar crowding present and the interpretation of the composite spectra that are obtained is often quite ambiguous. Nonetheless, it is very important to know metal contents as they indicate and are responsible for many features. For example, metal abundance will affect absolute magnitude determinations, which can be serious when doing main sequence fitting or assuming a unique luminosity for the brightest red giant stars. Decreasing a globular cluster's metal content will cause its observed main sequence to shift to the left (seem bluer) and put it further below the disk star main sequence.

There is also at least one other parameter besides [Fe/H] that can affect the positions in color-magnitude diagrams. The main contender presently is [CNO/Fe]. Red giant models are very sensitive to assumed CNO abundances [M1] as well as are theoretical main sequence turnoff luminosities [D1]. Large variations in CNO abundances have been observed between globular clusters and even between stars in the same globular cluster [M1]. This last result can be explained by either large differences in the primeval C/O ratio among the cluster's stars, successive waves of star formation forming abundance gradients or as the most likely possibility, sporadic variation from star to star of the thoroughness of mixing internally produced elements into the stellar envelope, which is the only place from which these elements can be directly measured.

Despite all of the difficulties, a great deal of information is available concerning metal abundances. Milky Way globular cluster metallicities satisfy $-2.2 \leq [\mathrm{Fe/H}] \leq 0.0$ [M1]. Globular clusters located near the galactic nucleus have nearly normal metal contents (relative to the disk population), while globular clusters in the halo are quite metal deficient, with metal abundances that are $\frac{1}{100}$ that of the Sun (although Harris and Racine report of one halo globular cluster that has a "high" metallicity [B1]). Actually, the situation is more complicated than this. Metal rich globular clusters are confined to a region near the nucleus while metal poor clusters are found to be distributed throughout the whole volume of the galactic bulge and halo [M1]. Thus, a great range in metal abundances is found is found for globular clusters near the galactic center. The trend of decreasing metallicity at increasing distance (from the galactic center) still seems to be dominant, however. Since the most distant globular clusters appear to be the oldest, this has led to the following proposed scenario [M1].

A rapid collapse of the halo may have occurred in the early history of the Milky Way. The oldest globular clusters formed at large distances from the galactic center and had low metal abundances. Due to their orbital motions, these clusters proceeded to fill the halo over the course of time. The stars in these clusters evolved, forming metals through nucleosynthesis and occasionally spewing some of the metals out when they turned nova or supernova. The regions nearer the galactic center would be preferentially enriched by these metals. Thus, as subsequent globular clusters formed progressively nearer the galactic center, they would form of progressively more metal-enriched material. Hence, the more metal rich globular clusters are now confined to smaller volumes near the galactic center. There is evidence that the disk is half as old as the globular clusters and so likely formed well after the collapse of the halo. Therefore, there was substantial time for the metal-enriched material from the dying cluster stars to settle into the disk, giving it a reasonably uniform and higher metal content than the globular clusters (the disk is also slightly richer in helium which enforces this conclusion). All of the above assumes that current metallicities are representative of the original metallicities and that the metallicity gradient is real.

Distances

The globular clusters in the Milky Way exhibit a great variation in distance from the galactic center, ranging from 2.0 kPc (NGC 6528) to 108.8 kPc (Palomar 3) (the nearest globular clusters to the Sun are NGC 6121 and NGC 6397 at 2.1 kPc) [P1]. For the globular clusters at distances beyond 20 kPc to be gravitationally bound to the Galaxy, a considerable mass in the halo is implied (the so-called dark matter) [B1]. The Sun's distance from the galactic center can be estimated from the distribution of globular clusters. This, it can be seen that accurate globular cluster distance estimates can provide much valueable information. Indeed, knowing globular cluster distances has proved crucial in determining the structure of the Milky Way.

Distances to globular clusters are determined best by either fitting cluster main sequences to the main sequence provided by nearby subdwarfs of known distance that have the same chemical composition as the cluster, or by assuming RR Lyrae variables have a constant visual magnitude (usually .6 ± .2 [R2]) and comparing the observed magnitudes with this value. Secondary distance estimates come from assuming constant values for the magnitudes of the brightest red giants, for the mean magnitudes of RR Lyraes and for integrated cluster magnitudes [H2]. A classical secondary distance indicator is the mean absolute magnitude of the 25 brightest stars in a globular cluster. There are a couple of major problems with this indicator, however [M1]. It depends vitally on the population of the globular cluster as the greater the number of stars, the greater is the likelihood of finding the very rare stars of the highest luminosity in the sample. Also, this indicator (and mean magnitudes in general) tend to depend (often strongly) on the metallicity. Of the 110 globular clusters for which comprehensive data is available, primary distance indicators have been used to determine the distances for 75, while the distances of the rest have been determined by various secondary indicators [M1].

Once globular cluster distances are known, the location of the galactic center can then be determined. Harlow Shapley first did this in 1918 and estimated a value for the distance between the Sun and the galactic center, R_0, of approximately 15 kPc. The best current estimates are $R_0 = 8.5 \pm 1$ kPc [H2] and the center lies in the direction of the constellation Sagittarius.

Three major methods have been used to estimate R_0 [H2]. The simplest is to plot z versus x (distance above the galactic plane versus distance from the Sun in the direction of the galactic center) for globular clusters. The average value of x, $< x >$, will yield a lower bound for R_0. This is a lower limit because the sample will be biased by the asymmetric distribution of globular clusters at low z, which will be predominantly on the Sun's side of the galactic center (objects on the other side at low z will usually be heavily obscured). This bias can be overcome by only sampling globular clusters with a z greater than some z_{min}. However, as z_{min} increases, there will be an increase in the statistical error due to the decreasing sample size. Harris chose $z_{\text{min}} \approx 2.5$ kPc as an optimal value. A second method is to look for a sudden cutoff in numbers in the z versus x plot. This will indicate the position of the galactic center (where there is a heavy visual extinction) is being approached. Finally, using a conventional mass model of the Milky Way, it has been determined that globular cluster orbits over a long period of time will develop a cone of avoidance over the galactic center. Thus, the location of the galactic center can be estimated by moving the vertex of a cone along the x-axis until the maximum cone size (or equivalently the minimum number of clusters in the cone) occurs.

The system of globular clusters is strongly concentrated toward the galactic center. The density distribution for globular clusters with $R \geq 3$ kPc (where R is the distance to the galactic center) appears to follow a $R^{-\alpha}$ law where $3 \leq \alpha \leq 4$ [M1]. This law also agrees with the distribution of halo stars. Globular clusters with $R < 2$ kPc cannot be seen. Oort using a dynamical model believes that there are approximately 55 globular clusters for $R < 1.25$ kPc and that their mass is nearly equal to the mass of globular clusters in the entire halo [M1]. Finally, it should be noted that the system of globular clusters seems to be pretty much spherical although the subsystem of metal rich globular clusters may show some flattening.

Variable Stars

2057 variable stars have been discovered in 105 globular clusters [H4]. However, no variable stars have found at all in 12 (perhaps 13) globular clusters (this may be due to selection effects). Five globular clusters contain more than 100 variable stars. About 90% of the globular cluster variable stars are RR Lyraes. Other variable stars found include type II Cepheids, Mira variables, RV Tauri stars, W Virginis stars and other semiregular and cyclical variables. In addition, 3 novae have been seen in globular clusters, 2 of which seem to be definitely members (the first one was noticed in 1860 by Auwers in M80).

Variable stars are relatively easy to detect and so have been extensively studied. However, care must be taken as for example, variables may turn out to be field stars—not really a member of the globular cluster that may lie in the background. Also, there are selection factors influencing the probability of discovery. In particular, short period variables and bright variables are more likely to be discovered. It probably is better to look at the frequencies of variables rather than at their absolute numbers [K4].

Since they are so common, RR Lyrae variables have been studied in great detail. RR Lyraes are good indicators of population and distance (for globular clusters both within and outside the Milky Way). They can also provide information about the degree of evolution, age and chemical composition of globular clusters. Traditionally, RR Lyraes have been mainly used as distance indicators. Since they belong to the horizontal branch, which is of nearly constant absolute magnitude, the distance to a RR Lyrae star, and hence to the globular cluster to which it belongs, will be determined by its apparent magnitude. According to Sandage [R2], the (B-V) boundaries of the RR Lyrae instability strip do not vary between globular clusters when due corrections for absorption and blanketing are made. Therefore, the positions of RR Lyraes in the color-magnitude diagram for a given globular cluster will yield the amount of interstellar absorption, ultraviolet excesses and other anomalies present for that globular cluster. It has also been found that the value of $< x >$ for metal rich globular clusters is 2.6 kPc larger than that for metal poor ones. This has led Harris to believe [H2] that the absolute magnitude of RR Lyraes is metal dependent. He uses $M_V = .6$ for metal poor clusters and .9 for metal rich ones. If this is so, this will have large repercussions in distance determinations.

RR Lyrae variables are found primarily in halo globular clusters with low metal abundances. RR Lyraes do not occur in globular clusters that have high metallicities (and red variables do not occur in globular clusters of very low metallicities) [K4]. An appreciable number of RR Lyraes have been found in the far outlying regions of globular clusters. As the RR Lyraes near a globular cluster often have the same characteristics as those found in the cluster itself, it is very likely that they originated in the globular cluster and so are useful for dissipation studies. It has been estimated [R2] that $\frac{1}{3}$ of all RR Lyraes not now in a globular cluster, originated in one.

Now, RR Lyrae variables are separated into two major groups: slow period ($\mathrm{RR_{ab}}$) and fast period ($\mathrm{RR_c}$) variables. If a globular cluster has stars from one of these groups, it generally has stars from the other one as well [H4]. Globular clusters have been classified into two groups (Oosterhoff groups) based on the relative frequencies and periods of their slow and fast RR Lyraes. Group I globular clusters have 82% $\mathrm{RR_{ab}}$'s and the mean periods of the $\mathrm{RR_{ab}}$'s and $\mathrm{RR_c}$'s (.53 day and .32 day, respectively) are shorter than those in group II (.65 day and .37 day, respectively) which consists of only 56% $\mathrm{RR_{ab}}$'s [R2]. The globular clusters in Group I also tend to have higher metal abundances and later spectra than those in group II. Thus, type I globular clusters are believed to be generally younger than those of type II. The variations in the periods of the RR Lyrae variables are believed to indicate the direction of stellar evolution, however, sometimes the measured period decreases or varies periodically as well as increasing so not everyone holds to this belief.

DYNAMICAL MODELS FOR GLOBULAR CLUSTERS

At this point, it would be useful to discuss some theoretical models for globular clusters. The most important one is a general dynamical model for globular clusters developed by Ivan King [K1,K2,K3,also some discussion in B1 and M1]. After a fairly detailed examination of this theory, some ideas on the evolution of the core region of globular clusters will be considered.

King has examined open clusters, globular clusters and dwarf elliptical galaxies and produced an empirical density law which can be used to describe all of these systems [K1]. This law has a minimum number of parameters (to be described below), therefore these systems are as similar as they could possibly be within scaling factors. This implies that each of these systems has been subjected to some kind of relaxation (regularizing) process at the time of their formation. There are two main mechanisms that could account for this relaxation. Either there was an initial violent mixing or mixing occurred over a period of time (called the relaxation time) through stellar interactions. The first mechanism would treat stars of all masses equally, producing a uniform distribution of masses, while the second mechanism would produce a difference in distribution between stars of high and low mass. Oort and van Herk have calculated that the relaxation time for the massive stars that dominate the center of a globular cluster is on the order of $1.5 \cdot 10^8$ years, so there has been considerable time (10^{10} years) for stellar interactions to have exerted a significant influence on the central structure of Milky Way globular clusters. Thus, globular clusters should show mass segregation while dwarf elliptical galaxies, with relaxation times of 10^{11} years, should not. However, segregation effects are most noticeable in highly concentrated globular clusters (which should have the longest relaxation times for globular clusters), while low concentration clusters have nearly indistinguishable distributions of bright and faint stars.

Now, nearly all the observed range of magnitudes in a globular cluster is inhabited by stars that have evolved from a small part of the original main sequence around the present day turnoff [K3], hence most of the (observable) stars in a single globular cluster have about the same mass. King in his model therefore assumed that all the stars in a cluster had the same mass. He also assumed that the distribution of stellar velocities was isotropic. Finally, since the mean free path in a cluster is many times the cluster's radius, over the short term spatial mixing will be much more of an effective mixing process than stellar interactions [K2], so King assumed that cluster structure could be represented by the solution to the steady-state Fokker-Planck equation which presumes that no stellar encounters occur (this is a modified isothermal model). Past stellar interactions will determine an initial velocity distribution for the model and this will in turn determine the model's spatial characteristics. The distribution must have a finite cutoff (escape) velocity (really a maximum stellar energy) which corresponds to the stellar density dropping to zero. A cluster has a finite boundary which is a tidal limit determined by the maximum differential shearing or tidal force experienced by the cluster. This will occur when the cluster makes its closest approach to the galactic nucleus in its orbit. Stars beyond this limit can be stripped off when the cluster is sufficiently close to the nucleus but any stars that lie below this limit will be retained.

The velocity distribution that results from solving the equation is virtually a Maxwellian distribution. The low velocity center of the distribution will correspond to the core of the density distribution and the high velocity tail will correspond to a spatial envelope surrounding the core. Deviations from the Maxwellian distribution will show themselves in the velocity distribution's tail (i.e. the outer envelope of the system). Thus, clusters should have similar cores while the outer envelopes can be expected to show the nature of the relaxation process. Examining the spatial distributions derived, it can be seen that the model fits open clusters, globular clusters and elliptical galaxies quite well. The model contains 3 independent parameters [K2]. One is the tidal limiting radius (r_t) described above. A second is the core radius (r_c) which is set by the cluster's gravitational binding energy. The last parameter is a number factor: for example, the cluster's total mass. The cluster's profile will be determined by the ratio of the tidal radius to the core radius (in other words, the central concentration). Thus, the central cores of all clusters have identical profiles except for scaling by number of stars and radius so, except for scale factors, clusters differ only in central concentration.

The drop off in density in the outer envelope of a cluster is actually due to a combination of tidal cutoff and an anisotropic distribution of velocities. The velocity distribution is believed to become more and more radial in the outer envelope based on the hypothesis that stars are ejected from the core every so often. These stars will assume predominantly radial orbits and because of the longer relaxation time in the relatively sparsely populated outer envelope of the cluster, many of these orbits will remain unaffected by stellar encounters and so retain their primarily radial orientation. An anisotropic velocity distribution will cause the cluster to have a larger tidal radius than is the case with an isotropic velocity distribution. From independent calculations of the galactic tidal field, an upper limit to the distance to which the envelope of a given cluster can extend can be set and this will allow an upper limit to the anisotropy of the velocity distribution to be determined. However, it should be noted, it is difficult to distinguish between anistropy effects and just choosing differing velocity cutoffs, so care must be taken in interpreting these results.

Once the density distribution has been determined, it is easy to determine the cluster stellar escape rate. It was determined by King [K2] that the escape rate is greater for clusters with small cores (low central concentrations) where tidal influences reach far in, and lower for clusters with extensive outer envelopes as the envelope will tend to inhibit escape. These two effects tend to compensate for each other so that the escape rate will be almost independent of the central concentration, being determined only by the total number of stars in the cluster and the strength of the tidal field. Stellar interactions will have a minor effect on the escape rate (as they will be rare in the outer envelope). Stellar interactions will cause a preferential depletion of low mass stars as these stars will frequently gain momentum out of an encounter and then will often have enough energy to be able to escape.

The loss of stars from a cluster will cause slow changes in the cluster's gravitational field. These changes will result in a gradual density readjustment, tending to cause the cluster to contract (the escaping stars will take more than their fair share of energy with them, lowering the average energy content of the stars remaining in the cluster). The cluster will try to maintain a steady of a state as possible and so it will evolve quasistatically through a sequence of such states over time. Opposing the tendency for the cluster to contract due to escaping stars will be a tendency to expand due to energy addition from mass lost by cluster stars during stellar evolution and occasional tidal shocks when the cluster passes through the galactic plane, close to the nucleus or near other large masses. The balance between the two opposing tendencies will determine the final course of the cluster's evolution.

Evidence for this theory includes noticing that the radii of globular clusters at the Sun's distance from the galactic center are about twice as large on the average as the radii of globular clusters nearer the galactic center [B1]. The central globular clusters apparently have been subjected to shearing by the Milky Way tidal force. Also, the globular cluster

E3 appears to have suffered severe tidal damage, having one of the smallest known ratios of r_t/r_c [V3]. In general, globular clusters with large r_t/r_c ratios have approximately 5 times the mean luminosity of those with small such ratios, definitely implying tidal forces really do remove stars from globular clusters [V3]. Finally, the extreme subdwarfs appear to have kinematic and spectroscopic properties identical to globular cluster stars [M1] and as it is rather implausible for them to have have formed singly throughout the low density halo regions where they are found, it is quite possible that these stars were born in globular clusters which subsequently dissolved. Since the mass density of extreme subdwarfs is orders of magnitude larger than the mass density of globular cluster stars (at the Sun's distance to the galactic center), this could imply that only a small fraction of the original globular cluster population is left.

The most basic part of a globular cluster is its core. The evolution of the core is less understood than the evolution of the outer envelope, so there are more theories in circulation about core evolution than in the latter case where Ivan King's theory stands out. The core can be treated mathematically as an isolated system which looses mass and energy at a constant rate or Monte Carlo methods can be used [H3]. The results imply that the cores of some globular clusters have already collapsed and that the core will collapse due to escaping stars on a much shorter time scale than the outer envelope. It is likely that there are remnants of stars in the core which have completed their evolution and so core collapse may not involve the bright stars that are now observable. According to the Monte Carlo models, stars in the core will tend to combine into multiple star systems [B1] which require extra energy to maintain. Therefore, along with stellar evaporation, binary formation will be primarily responsible for core collapse. Core collapse will be somewhat mitigated, however, by encounters between hard (tightly bound) binaries and unattached stars which will tend to result in the release of kinetic energy [H3]. Eventually, though, binary-binary interactions will likely destroy enough of the core binaries to bring on further collapse.

Thus, the final likely fate of the core of a globular cluster, if it is not torn apart too quickly by tidal forces, is either the formation of a collection of binary star systems or the formation of a black hole. Binary systems can prevent further collapse as described above and black holes can arrest core collapse if they are sufficiently massive (100–$1000\mathrm{M}_\odot$) by accreting free gas from the interstellar medium in the core (some of which may be mass lost through stellar evolution of the core stars) and emitting energy into it. Core collapse has not been detected observationally, however (globular clusters have smooth central distributions with a typical core radius of 1 Pc), except possibly in M15 which shows an enhanced bright center (enhanced over an isothermal core) [K3,H3].

Some astronomers have speculated that globular clusters that have x-ray sources may be experiencing core collapse. The 7 observed globular cluster x-ray sources have preferentially been found in the cores of globular clusters with large escape velocities, small relaxation times and high central concentrations, all of which indicate an advanced state of evolution [J1]. Six of these x-ray sources show steady emissions and one is a 'Rapid Burster'. 3–5 of the sources, including the Rapid Burster, show type I x-ray bursts (soft spectra and no periodic pulsations—type II x-ray sources show hard spectra and often periodic pulsations and are usually associated with population I objects like rotating neutron stars). Lewin believes [L1] that type I x-ray sources in globular clusters are members of the galactic bulge x-ray sources found outside of globular clusters and they may be either neutron stars or black holes of ~ 1–$5\mathrm{M}_\odot$ (the bursts may be due to thermonuclear flashes on the surfaces of neutron stars). He finds that the bursts of the Rapid Burster best fit a blackbody spectrum coming from an object of radius 8 ± 2 km. About 5% of the galactic x-ray sources are located in globular clusters but globular clusters make up only about 0.1% of the galactic mass, thus x-ray sources are 100 times more likely to be found in a globular cluster than anywhere else. Therefore, the conditions inside a globular cluster must somehow be special for creating x-ray sources and this may well be due to core collapse.

EXTRAGALACTIC GLOBULAR CLUSTERS AND ORIGINS

Globular clusters have been observed in many galaxies besides the Milky Way. Reasonably detailed information is available for globular clusters in Andromeda and the Large Magellanic Cloud, while fragmentary data has been obtained for globular clusters in 6 other dwarf members of the Local Group and 15 members of the Virgo Cluster of galaxies. Preliminary data is available for globular cluster systems in M81, NGC 3115, NGC 5218, and in galaxies of the Fornax I and Hydra I Clusters (which lie beyond the Virgo Cluster) [R1]. Observing extragalactic globular clusters is not easy. The closer ones exhibit small diffuse images which can be confused with very distant background galaxies and images of open clusters and knots of nebulosities. More distant extragalactic globular clusters appear stellar and may be confused with field stars (however, multicolor photometry can be used to enhance the contrast between the two [G3]).

Among the globular clusters of the Local Group, a variety of characteristics is exhibited. The features of the halo globular clusters in Andromeda are quite similar to those found in the Milky Way, with perhaps a moderately higher average metallicity [R1] (although this is disputed by Hanes [H1]). This is not true, however, for the globular clusters in the Magellanic Clouds. No Oosterhoff type II globular clusters have been found in them [G2]. Also, there is a clear division of Magellanic Cloud globular clusters into two groups [G1]: red and blue. The former type is similar to Milky Way globular clusters. The blue clusters have masses of 10^4–$10^5\mathrm{M}_\odot$ (similar to the masses of the smaller Milky Way halo globular clusters) and estimated ages of only 10^7–10^8 years [F1]. These systems are thus probably young globular clusters and show no counterpart in the Milky Way. Also, since they have relaxation times around $5 \cdot 10^8$ years, they most likely were regularized in some kind of initial reaction [F1]. These blue globular clusters have been primarily found in the outer parts of the Large Magellanic Cloud where the gas density is fairly low, so it is possible that they may have been formed by a different mechanism than red (Milky Way type) globular clusters. Finally, the Small Magellanic Cloud contains many more globular clusters than IC 1613 [V3], also a Local Group irregular galaxy, indicating that large differences in globular cluster frequency can occur.

Also associated with the Local Group are several dwarf spheroidal (actually elliptical in some cases) galaxies. Nine of these dwarf galaxies, along with the Magellanic Clouds, make up a retinue of satellite systems surrounding the Milky Way. The dwarf galaxies appear to be purely population II systems (unlike the Magellanic Clouds) and one of them (Fornax) has as many as 6 globular clusters of its own [Z1]. Three of these dwarf spheroidal galaxies (Leo II, Draco and Ursa Minor) are similar to Milky Way globular clusters in terms of mass and luminosity but have much larger volumes and correspondingly lower densities (and very long relaxation times, on the order of 10 billion years). The color-magnitude diagrams of the dwarf galaxies resemble those of globular clusters and they all appear to have low metal abundances [Z1]. This has led some astronomers to suggest that these galaxies and the most distant halo globular clusters of our Galaxy are the tidal debris of a past close encounter between the Milky Way and the Magellanic Clouds but so far, there is very little supporting evidence. One place where the dwarf galaxies differ from Galactic globular clusters in an important respect is their variable stars [Z1]. The dwarf galaxies can be classified into Oosterhoff groups by their RR Lyrae variables, but certain correlations satisfied by Galactic globular clusters in each group are not obeyed by the dwarfs. Also, the dwarf galaxies do not contain any type II Cepheids, but they do contain a class of unusual Cepheids which are very rare in Milky Way globular clusters. It therefore appears that globular clusters associated with the Milky Way have 'family traits' which differ systematically from those in globular clusters in the Magellanic Clouds and the dwarf spheroidal galaxies [V2].

Now, some general observations about globular clusters (Galactic and extragalactic) can be presented. Globular clusters show large differences in frequencies (number of globular clusters per unit of luminosity) between galaxies. An example was presented above for two irregular galaxies in the Local Group, and the same can be seen with elliptical galaxies. For example, M87, which is near the center of the Virgo Cluster, is very rich in globular clusters, while NGC 5128, a field galaxy, is poor in them (this may be due to the relative locations of these galaxies) [V3]. The brighter and larger galaxies tend to possess more globular clusters than the dimmer and smaller ones, although there are significant exceptions [R1]. M87 is particularly noteworthy in that it exceeds the average number of globular clusters for its luminosity by an order of magnitude! Being near the center of the Virgo Cluster, it is in a favorable position to accrete globular clusters; also, M87 may have an abnormally large mass.

Most luminous galaxies have huge halos of globular clusters. For example, the globular cluster systems around two giant elliptical galaxies have observed radii of 40 and 100 kPc and may stretch over MPc diameters, which becomes comparable to the intergalactic separations themselves [R1]. Thus, globular cluster systems have significantly larger effective radii than do the light distributions of the spheroidal components in the galaxies with which they are associated. This suggest that globular clusters became differentiated structures at a time preceeding the formation of the current spheroidal component stars (however, other people believe differently).

Other general observations include that the radial density distribution of globular clusters around a galaxy appears to follow an $R^{1/4}$ law (as has been observed in the Milky Way, Andromeda, M49 and M87) [R1]. There is a similarity between this distribution and the density gradient within elliptical galaxies [V2]. This implies that the halo has a structure comparable to an elliptical galaxy, although the halos of spiral galaxies may show different (larger) enrichment gradients than are found in the ellipticals. More massive galaxies tend to have redder globular clusters of higher average metallicity than those found in smaller galaxies [R1]. From theoretical models, it appears that metal rich globular clusters are brighter than metal poor ones (metal rich clusters may be able to convert mass more efficiently into stars and may also have more absolute numbers of stars as the stars will evolve more slowly off the main sequence). The smallest galaxies contain globular clusters of the lowest metallicities, while the results for halo globular clusters in large galaxies are mixed. Metallicity gradients, where they exist, occur in such a fashion that the most distant globular clusters are the poorest in metals [R1]. Also, it has been observed that there is a population of very late type stars present in galaxies (even in dwarfs), but which are not found in globular clusters (even in the most metal rich ones) [F2].

A final important observation is that even though galaxies differ in luminosities (and thus probably masses) by as much as a factor of 1000, the globular clusters contained by each galaxy have essentially the same average absolute visual magnitude of $\overline{M}_V = -7.4$, irrespective of the size or type of the galaxy [R1]. Within a single galaxy, however, the absolute magnitude of single globular clusters may range from $M_V = -10$ to -3. Actually, the results may be even more comprehensive. The luminosity functions for globular clusters in the Milky Way and Andromeda have been demonstrated to be virtually identical [H1]. There is strong evidence that the globular cluster luminosity functions are closely similar in all the galaxies of the Local Group and also among the elliptical galaxies of the Virgo Cluster [H1]. Therefore, Hanes believes [H1] that globular cluster luminosity functions may be universal, scaled only by the total population of globular clusters in a galaxy. Also, the total globular cluster population associated with a given galaxy will be, to first approximation, directly proportional to the mass of that galaxy (with some exceptions).

This last observation shows that globular clusters can be particularly useful in galaxy distance determinations. This is so because the distance to a galaxy could be determined from a single calculation rather than invoking a chain of indicators. Also, the distance would rely exclusively on population II indicators, and this would serve as a check on the population I indicators currently used. In the past, the distance to galaxies has been calculated by comparing mean integrated magnitudes, the maximum absolute magnitude of a globular cluster associated with a galaxy, and the same but empirically corrected for the fact that brighter galaxies possess larger numbers of globular clusters. It seems that now, it would be best to use full globular cluster luminosity functions to make distance determinations. In particular, the difference between the apparent magnitude of the horizontal branch and the apparent integrated magnitude of the globular cluster to which the horizontal branch corresponds is independent of interstellar absorption, assuming the absorption is not patchy on scales smaller than the globular cluster [H1]. So, assuming a value for the absolute magnitude of the horizontal branch, the absolute integrated magnitude of the globular cluster can be determined and hence its distance, using the absorption independent difference for absolute magnitudes. Then, using the same technique once again with the absorption independent difference between globular cluster and associated galaxy integrated magnitudes, the absolute magnitude of the galaxy itself can be determined. This result can then be used to set a zero point in the Hubble diagram and therefore establish the cosmic distance scale.

Finally, it is time to consider origins. Globular cluster properties can be helpful in deciding between alternative theories of galaxy formation. Four major theories have been proposed to explain the origin of the Milky Way [V2]. The first suggests that the first bound systems to have formed in the expanding universe were clouds of mass similar to that of globular clusters. These protoclusters subsequently banded together to form protogalaxies. This theory, however, does not explain the globular cluster metallicity gradient nor why the metallicities of globular clusters depends on the luminosity (or mass) of their parent galaxies. Also, it does not explain why only .1–1% of the original globular cluster size clouds actually ended up as globular clusters. Finally, no large numbers of intergalactic globular clusters are found, contrary to what seems likely from this theory. The second theory proposes that the Galaxy was formed by the merger of dwarf galaxies, but this does not seem reasonable considering the difference in properties between the Milky Way globular clusters and the nearby dwarf spheroidal galaxies. The third theory suggests that the galaxy was formed from a lumpy protogalaxy. In other words, matter may have been highly clumped on scales much smaller than an entire protogalaxy. Star formation took place first in the densest subsystems which later merged when the halo collapse took place. Alternatively, high velocity collisions between dense clumps of matter might have triggered bursts of star formation. The last theory is related, in that it proposes that the Galaxy formed from a homogeneous protogalaxy in which gas and stars collapsed together in free fall.

Some astronomers believe that galactic nuclei were formed by the accumulation of globular clusters dragged in by dynamical friction, but observations of the nuclei of Andromeda, M32 and M33 indicate that this was not so in these cases [V2], and so nuclei formation is probably not directly related to the existence of globular clusters. Very circumstantial evidence exists that globular clusters were formed before quasars [V2]. The observation that many globular clusters have low metal abundances whereas there is no strong evidence that quasars are metal poor, and also that quasar heavy-element abundance ratios are similar to the Sun's seems to indicate that quasars occur in regions that have been polluted by at least one generation of evolving stars, perhaps from globular clusters.

The final question is, are globular clusters primordial? That is, did globular clusters form from density fluctuations present at decoupling on a time scale much shorter than the time scale for formation of the galaxies [G3]? Van den Bergh [V2] believes so, and thus that globular clusters survived the coalescence of ancestral protogalaxies. Gunn, however [G3], believes that (Milky Way) globular clusters were formed in some unspecified manner during the early collapse of our Galaxy. At this time, nothing is certain.

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