LUMINOSITY FUNCTIONS AND EVOLUTION OF GLOBULAR CLUSTERS

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Why are globular clusters so important for astronomy ? Here are some reasons. (i) Globular clusters are the oldest luminous objects in the Galaxy. They are samples from the early chemical evolution of the Galaxy, as the metal abundance [m/H] rose from about -2.5 to about -0.5. (ii) They are large enough to give a statistically significant data set for stellar evolution studies over this whole abundance range. (iii) Their stellar dynamics is very inviting; globular clusters are relatively simple structurally, so there seems to be a real opportunity for a fairly complete understanding of their internal dynamics. (iv) Some of their chemical and dynamical problems are similar to those of galaxies (eg the large clusters 47 Tuc and ω Cen show galaxy-like radial abundance gradients). These problems are much more tractable for globular clusters, because we can measure directly the chemical abundances and kinematics of individual cluster stars.

I believe that ST will have a really profound effect on the course of globular cluster studies, in many areas. I will talk about a few areas now: others will come up during the discussion. Most of the urgent problems of globular clusters require observations of faint stars, and this is where we will see ST at its best.

I. LUMINOSITY FUNCTIONS

a) The old halo clusters

The initial mass function for recent star formation in the galactic disk appears to be fairly uniform. It may not have been so uniform at the time of formation of the oldest galactic populations. For example, the apparent existence and unknown content of dark galactic halos suggests that

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star formation did not always proceed with the present IMF. This makes the mass functions of globular clusters particularly interesting, because they were probably among the first objects to form. Progress in this area is fairly recent, because the nearest globular clusters are in the South, and only three clusters have been studied in detail so far. Da Costa (1977) showed that the slope x of the IMF varies from about 0.9 for NGC 6397 through 1.5 for NGC 6752 to 2.9 for 47 Tuc ($x = 1.35$ for the Salpeter function). What cluster properties does x correlate with ? This is not yet clear: for Da Costa's three clusters, x increases with chemical abundance and cluster mass. Probably chemical abundance is the important variable for the IMF. The clusters M15 and M92 have similar abundances and luminosity functions to those of NGC 6397, but they are significantly more massive (Sandage and Katem 1977, van den Bergh 1975).

What can ST contribute to the study of globular cluster mass functions ? The small image size of the WFC wins twice here. It allows the detection of faint stars against the sky background, and it greatly reduces crowding problems. Crowding is the analog of confusion in radio astronomy. It causes star counts to become inaccurate when a significant fraction of the field is covered by stellar images. For example, with large groundbased telescopes, crowding problems become important for star densities of about 100 stars/ sq arcmin. At magnitude $V = 22.5$, the galactic background alone is a few tens of stars/sq arcmin in typical globular cluster fields, so detailed luminosity function work from the ground is obviously limited to the outermost parts of the clusters. With ST, crowding problems become important at about 10^4 stars/sq arcmin: the galactic background is significantly less than this, even at the WFC limit (see van den Bergh's talk), except for some fields in the galactic plane.

Here are three obvious areas in which ST can make a really significant contribution to this problem of the stellar content of globular clusters.

(i) For the closest clusters, it will be possible to derive the luminosity function down to $M_V = +15$ ($\mathfrak{M} = 0.1\mathfrak{M}_\odot$). Reliable data on the mass function down to this low mass limit would be very valuable, both for its own interest and for dynamical modelling.

(ii) The data we now have on cluster luminosity functions is limited by crowding problems to the outer parts of the clusters. To derive the integrated luminosity function of a cluster, model-dependent corrections are required. These corrections depend on the level of thermodynamic equilibrium attained by the cluster, and this is not yet well understood. Also, some clusters have radial abundance gradients, which further complicate the problem. With ST it will be possible

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to measure the luminosity function directly, almost in to the core of even the most concentrated nearby clusters, down to $M_V = +9$.

(iii) There remains the problem of the slope x of the cluster mass functions: does it depend on the cluster's chemical abundance? It seems very important to study a few more metal-rich clusters, to see if their mass functions are also steep, like that of 47 Tuc. This is a ST problem: although there are several metal weak clusters close enough for groundbased luminosity function work, there are no more nearby ($m-M < 14.5$) metal rich ones at galactic latitudes $|b| > 15^\circ$.

b) LMC clusters

Unlike our galaxy, the LMC contains globular clusters of all ages. The youngest, with ages of about 10^7 y, are globular-cluster-like in structure and total mass, and they have no known counterpart in the Galaxy. For these young clusters, it is possible to derive the mass functions from the ground, for the mass interval $1.2 < \mathfrak{M} < 6\mathfrak{M}_\odot$: for a sample of young clusters of similar ages, chemical abundance and environment, the slope x of the mass function can take any value in the range $0 < x < 3$ (Freeman, 1977). It would be very interesting to know whether the lower main sequence mass function is equally unpredictable. Again, crowding makes further groundbased work difficult, because the background density of LMC stars is already about 100 stars/sq arcmin at V = 22.5, even in the outer parts of the LMC. With ST it will be possible to measure the luminosity functions of these young clusters down to $M_V = +9$ ($0.4\mathfrak{M}_\odot$). The total observable mass range (about 6 to $0.4\mathfrak{M}_\odot$) will then overlap the presently observable mass range for the nearest galactic globular clusters (0.8 to $0.3\mathfrak{M}_\odot$). Direct comparison of the mass functions for these old and young globular clusters will then be possible, and it will be interesting.

c) The dwarf spheroidal galaxies

The chemical abundances of these old systems are like those of the halo globular clusters. However their mean stellar density is very low. Star formation in such low density systems is rather interesting, and it would be well worth deriving their mass functions, to see if the mass functions are like those observed for the globular clusters. The dwarf spheroidal galaxies are too distant for this to be done from the ground. With ST it will be possible to reach $M_V = +9$ for the Draco system, and about +7 for Fornax. The Fornax dwarf will be particularly important, because it contains a few globular clusters of its own. It will be very interesting to compare the mass functions of its clusters

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with that of the Fornax galaxy itself.

II. CHEMICAL TOPICS

a) Individual clusters in the Galaxy

Several globular clusters are now known to be chemically inhomogeneous, so there is something to understand about the chemical evolution of individual globular clusters. At least two clusters [47 Tuc (Norris and Freeman 1979) and ω Cen (Norris Freeman and Seitzer, to be published)] have radial abundance gradients like some galaxies. For ω Cen in particular, there are now observations of about 200 member stars from the cluster center out to its tidal radius. The radial change of CN in this cluster is very similar to the radial change of globular cluster abundances in our Galaxy. Stars in the inner parts of the cluster show a wide range in CN, while those in the outer region are predominantly CN-weak; ie ω Cen appears to have its own low abundance halo.

The obvious spectroscopic experiments, needed to investigate this chemical structure within individual clusters, can be made from the ground. I have no immediate suggestions for ST spectroscopy in this area. But I would ask you to keep in mind that some clusters have chemical gradients like galaxies, and that the problems of their chemical evolution are interesting, and are probably more tractable than those in galaxies because we can observe individual cluster stars.

I have already discussed the apparent dependence of the mass function on chemical abundance. It would be very interesting to observe this within an individual cluster. The ideal object for this experiment is ω Cen. It shows a very clear radial abundance gradient. Also, its relaxation time is very long, so the approach to thermal equilibrium should not produce any significant radial change in the mass function. Crowding problems prevent us from measuring the radial dependence of the mass function from the ground, but this experiment should be straightforward with ST. The main problem will be to establish the galactic background luminosity function properly, because the numbers of background and cluster stars (per unit area) are about equal at half the cluster's tidal radius.

There is some evidence that the dwarf spheroidal galaxies are chemically inhomogeneous (eg Zinn 1978), and it is very important to find out whether they show heavy element inhomogeneities and radial chemical gradients. The

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measurement of Ca abundances in RR Lyrae stars is a very direct and well calibrated probe of the heavy element abundances in metal-weak systems. Several dwarf spheroidal galaxies are rich in RR Lyrae stars, and are close enough for observation with the FOS. A resolution of 10^3 and S/N of 10 are adequate for this work

b) Young globular clusters in the LMC

The chemical inhomogeneity and chemical gradients in some old halo clusters suggests that chemical enrichment occurred during their formation. It would be interesting to see if there is any evidence for this enrichment in the young globular clusters of the LMC. These systems have ages of about 10^7 y, and their color-magnitude diagrams show evidence for an internal age spread of about 5.10^6 y (Robertson 1974), which is comparable to their free fall time. So, if enrichment does occur during cluster formation, then the stars forming later should be more enriched.

These young clusters have masses in the range 10^4 to 10^5 $\mathfrak{M}_\odot$. For halo clusters in this mass range, the chemical inhomogeneities reported so far are in CNO only, and not in the heavier elements. It would probably be most useful, and give a fairly unambiguous result, to observe CN in the late F and early G main sequence stars of these young clusters. These stars have $V \approx 22.5$, so are within reach of the FOS in its $R = 10^3$ mode.

c) Extragalactic clusters

There is already some information about the distribution of globular cluster abundances with radius in our galaxy and M31 (eg Searle 1978, Searle and Zinn 1978). This gives a useful constraint on pictures of galaxy formation and chemical evolution. It would be very valuable to have similar data for the globular clusters around a few elliptical galaxies of different masses, because the metal abundance of elliptical galaxies appears to depend on mass. The Searle-Zinn technique gives an estimate of cluster abundances from low resolution spectrophotometry. With the FOS at R = 100, it should be fairly straightforward to observe globular clusters around the Virgo cluster ellipticals.

III. DYNAMICAL TOPICS

a) Cluster rotation

For elliptical galaxies, the ratio of their rotational velocity to their velocity dispersion is smaller than one would expect from their observed flattening (eg Illingworth,

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1977). Most galactic globular clusters are nearly spherical: the most flattened ones have axial ratios of about 0.8. Omega Cen is one of the flattest, and we know now that it is rotating sufficiently rapidly to produce its observed flattening (Freeman, to be published). In the Magellanic Clouds, however, there are a few highly flattened globular clusters (eg NGC 121, NGC 1978), and it would be very interesting to know whether <u>their</u> flattening is associated with rapid rotation. Rapid rotation here means about ± 5 km/s, which is measurable. Accurate velocities (± 2 km/s) would be needed for about 50 stars at about V = 19. This would be a difficult experiment from the ground. With the FOS at R = 10^3, velocities of this accuracy should be possible (from recent groundbased experience); the observations should take 5 to 10 minutes per star.

b) Thermal equilibrium

Dynamical models are very important for interpreting the observed stellar content and kinematics of globular clusters. For example, there is no other way at present to estimate their content of nonluminous matter, like white dwarfs and neutron stars. To make these dynamical models, some assumptions must be made about the dynamical state of the clusters. One very important assumption is that of thermal equilibrium. However we do not really know observationally how close the clusters are to thermal equilibrium. We would expect that systems with the shortest relaxation times should be most nearly in thermal equilibrium. However 47 Tuc, which has a central relaxation time of about 2.10^8y, shows a very clear radial gradient in CN. It is not at all clear how this gradient has survived the effects of relaxation, and it seems that our understanding of relaxation and the approach to thermal equilibrium may not be complete.

There are two fairly direct ways to estimate observationally how close a particular cluster is to thermal equilibrium.

(i) Mass segregation: the lightest stars should be least concentrated to the cluster center. This is very difficult to observe from the ground, because crowding problems limit observations of faint stars to the outer parts of the cluster. With ST it will be possible to derive the radial distribution of faint stars almost in to the cluster centers (see section I.a). Also the accessible mass range will be significantly larger: 0.8 to $0.1\mathfrak{M}_\odot$ for the nearest clusters, compared to 0.8 to $0.3\mathfrak{M}_\odot$ from the ground.

(ii) Velocity dispersion: this is approximately proportional to $\mathfrak{M}^{-\frac{1}{2}}$ ($\mathfrak{M}$ is the stellar mass) for a cluster in thermal equilibrium. For the nearest clusters, we have a baseline of a factor 2 in mass between the red giants and the dwarfs with V = 20.5. The experiment would need accurate velocities

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(± 2 km/s) for about 100 dwarfs, to get adequate precision. This is well within reach of the FOS (cf III.a)

c) Extragalactic clusters as probes of galactic potentials

From the radial distributions of number density and velocity dispersion for the globular cluster system in a galaxy, it is possible to derive some useful constraints on the potential field of the parent galaxy. In practice this is a fairly substantial program for galaxies outside the local group. Velocities accurate to about 30 km/s are needed for about 100 clusters with magnitudes mostly fainter than V = 21. Observations with the FOS at $R = 10^3$, S/N = 3 would be adequate, but would be timeconsuming because the clusters are extended objects.

There is another way to use the clusters as probes of the galactic potential. The tidal radius of a cluster is set by the tidal field it experiences near perigalacticon. From the observed tidal radii of clusters far from the galactic center, we can derive upper limits on the galactic tidal field at the location of the cluster. (We need to know the M/L ratio for globular clusters, which is now fairly well established). If some of these distant clusters are in approximately circular orbits around their parent galaxy, then the derived upper limit on the tidal field is close to the true value of the tidal field. There is good evidence now for globular clusters in our galaxy that some of the outermost clusters are really in orbits of low eccentricity, so the tidal radii of clusters in extragalactic systems offer a fairly straightforward way of estimating the galactic potentials in the outer parts of the galaxies. This will be particularly useful for ellipticals, for which no other direct method is known at present. Observationally the tidal radii can be measured from direct ST images of the clusters: typical tidal radii are about 1 arcsec at the distance of the Virgo cluster.

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DISCUSSION

Illingworth (Discussion leader): Can we take questions first ?

King: My experience in measuring tidal radii of globular clusters is that I get the best results by extending the counts to $M \approx +3$ and not relying on the red giants alone. It will only be possible to measure the red giants in globular clusters at the distance of the Virgo cluster.

Freeman: At the distance of the Virgo cluster, individual stars will not be resolved and we will see only the diffuse distribution of red giants. I am basing my remarks on studies of globular clusters in the Magellanic Clouds where the photometrically determined tidal radii agree well with those determined by star counts.

King: Is a resolution of $R = 10^3$ adequate for measuring accurate velocities in globular clusters ?

Freeman: My experience with the 3.9 metre Anglo-Australian Telescope is that a resolution $R = 4 \times 10^3$ is very much more than is necessary. Most of the scatter in the velocities is cosmic.

Hemenway: Even the nearest globular clusters are too distant to have their parallaxes measured by ST. However, over a period of 10 years it should be possible to measure their internal motions. With an accuracy of 2×10^{-3} arcsec over a period of 10 years, internal motions of km s^{-1} are measurable at a distance of 10 kpc. Similar studies are possible using the Yerkes plates taken at the turn of the century. However, they only enable the top of the HR diagram to be studied and with ST it will be possible to extend these studies to fainter stars, enabling internal motions as a function of star mass to be studied. It will also be possible to measure the absolute motions of the globular clusters by combining radial velocity measurements with mean proper motions so that their orbits in the Galaxy can be measured precisely.

Gallagher: Are there advantages in making star counts at 1 μm where you will be less sensitive to the problems of line-blanketing in individual stars ?

Illingworth: Yes. It is very much easier to use I-R colours and hence it is very important to use the red capability of the Wide Field Camera. The gain in going into space is that from the ground, the sky is very bright in I.

J.N. Bahcall: Garth Illingworth has asked me to describe briefly the potentialities of ST for detecting massive black holes that might exist in globular star clusters. My remarks will be based on work done earlier by Dick Wolf and myself (Bahcall and Wolf, Ap. J., 209, 214, 1976 and

Ap. J. 216, 883, 1977 paper I and II, respectively) The motivation for the work is that two-body relaxation times in clusters can be much shorter than stellar evolution times, suggesting something dramatic may have happened. The basic assumption is that there is a point source of gravitational potential with a mass M_{BH} that satisfies $M_{STAR} << M_{BH} << M_{cluster\ core}$. (This "point-source" could be a condensed subcluster of stars as long as its dimension is small compared to the core dimension.) The equilibrium star distribution was derived both analytically and numerically, using approximations whose accuracy was also studied and found to be satisfactory.

The predicted velocity dispersion and the density cusp were derived and discussed in §V of Paper I and §VI of Paper II. Also given (in equation 103 of Paper I) was the expected mean displacement of the massive black hole from the centre-of-light of the star cluster. Neta Bahcall and her associates (see e.g., N. Bahcall and M. Hausman Ap. J. 213, 93, 1977) have derived upper limits of $M_{BH} \lesssim 10^4 M_\odot$ on the basis of data obtained with ground-based telescopes. ST observations would be sensitive to masses $M_{BH} \gtrsim 5 \times 10^2 M_\odot$. It will be important to obtain star counts with exposures of various durations and deep photometry in several colors, as well as velocity dispersion both inside and outside (necessary for setting the distance scale of the problem) the stellar core.

King: I would first like to direct some remarks specifically to what ST can do for globular clusters. One important area is the faint end of the luminosity function. Most of the mass of a globular cluster resides in stars too faint to observe from the ground. We can infer this from ground-based observations of velocity dispersions and core radii, but with ST we will be able to observe faint stars directly - both the red dwarfs and the white dwarfs. With ST resolution we will also be able to look into the centers of clusters. Of particular interest are the clusters with dense centers - both those that have X-ray sources and those that do not.

Meanwhile there is much current discussion of the X-ray globulars, often with the suggestion that such a cluster may have a black hole at its center. Let me remind you that neutron stars can do equally well, both in providing an X-ray source and in giving extra mass density that can explain the brightness excess at the center of M15. With regard to the latter problem, I have been looking at the other high-density clusters, getting material for velocity dispersions and for central light distributions. For what it is worth at a very intermediate stage of the reduction, I have not yet seen the M15 phenomenon in any other cluster.

Castellani: I would like to stress the importance of ST observations in the study of stellar evolution in Galactic and extragalactic globular clusters. The main point is that, by observing globular clusters, we

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observe the oldest objects we know in our Galaxy and at the same time, a very general component of the Universe. We must remember that there is a major "mystery" in our understanding of stellar evolution - where do the heavy elements which we find in population II stars come from ? In my opinion, it is difficult to escape the conclusion that we cannot claim to understand the evolution of the Universe before solving in detail such problems. In this context, observations of globular clusters have to be used in two steps. The first is to compare theory with observation in order to understand how far we can rely on theory, i.e., how well we understand the physical mechanisms at the basis of stellar evolution. The second step is to use theory in interpreting the observed evolutionary history of clusters, i.e., of obtaining "archaeological" evidence on the evolution of the Universe. My personal feeling is that by the time ST is launched, we will know how to apply such decodification procedures. We will be able to derive ages and primordial chemical compositions for every well-studied cluster, meaning all those for which the main sequence and later evolutionary phases have been exhaustively studied. At least, ST will give us quite a lot of information about the evolution of our Galaxy and of the Local Group.

In this context, I wish to draw attention to the problem of white dwarfs. There is no doubt that white dwarfs in globular clusters will be observed by ST if their luminosities and colours are the same as those indicated by current theory. If this turns out to be the case, we will rely more and more on the theoretical framework and we will obtain unique information about evolutionary parameters such as the amount of mass-loss and the effects of stellar rotation.

Finally, I note the recent suggestion of a very luminous white dwarf in the globular cluster NGC 6752 which is completely outside the range of theoretical expectations. Some astronomers of an Aristotelian frame of mind claim this is "impossible". I feel it is rather "highly improbable" when one takes into account the contamination of the cluster field by quasars. It will be most interesting if the original suggestion is true because every time we find something new, we learn a bit more about the Universe. I have no doubt that ST will also solve this important problem.

Gallagher: I would add that the problem of anomalous blue stars in globular clusters such as the B3 star in 47 Tuc is a general problem and may be studied by ST i.e. those blue stars which lie outside the normal horizontal-branch morphology.

Castellani: Some of these anomalous stars may be due to the effects of stellar rotation.

Gallagher: There is also the possibility that they are members of binary systems.

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Freeman: The anomalous blue stars are not so anomalous. They can be understood in terms of post-asymptotic giant branch evolution and are the analogues of the nuclei of planetary nebulae.

Illingworth: I would like, finally, to emphasise the use of globular clusters in estimating the masses of early-type galaxies. There are problems in using most of the other methods of measuring masses in these galaxies. The use of globular clusters to measure velocity dispersions and their variation with radius in the galaxy provides not only mass estimates but important evidence about the chemical and dynamical evolution of these systems. It is evident that the study of globular clusters with ST will have important repercussions for many aspects of the evolution of stars and galaxies.