GLOBULAR CLUSTERS AT HIGH REDSHIFT

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ABSTRACT

Globular clusters will be present at high redshifts near the very beginning of the galaxy formation process. Stellar evolution ensures that they will be much more luminous than today. We show that the redshift distribution at nanojansky levels should be very broad, extending up to the redshift of formation. A bracketing range of choices for the redshift of formation, spectral energy evolution models, and population density evolution leads to the conclusion that the sky densities should be around $10^7$ per square degree at 1 nJy ($m_{AB} = 31.4$ mag) in bands around 4 $\mu$m. Such high sky densities begin to present a confusion problem at these wavelengths to diffraction-limited 6 m class telescopes. These starlike, low metallicity clusters will be a significant foreground population for “first light” object searches. On the other hand, they are an exceptionally interesting “second light” population in their own right. Depending on the details of galaxy assembly, the clusters will have a noticeable cross-correlation with galaxies on scales of about 20″ or less, depending on the details of the buildup of galaxy assembly after globular cluster formation. High-redshift globular clusters will be an accessible, direct probe of the earliest stages of the formation of galaxies and the buildup of metals in the universe.

Subject headings: galaxies: clusters: general — galaxies: interactions — galaxies: star clusters — globular clusters: general — stars: formation

On-line material: color figures

1. INTRODUCTION

Globular clusters contain some of the oldest stars in the universe and have long been vital clues to the earliest phases of the star formation in galaxies (Searle & Zinn 1978; Harris 1991; Côté, Marzke, & West 1998). In our own Galaxy, the known globular clusters are very old (VandenBerg 2000), but there is evidence that they can form at lower redshift in suitably extreme conditions generally associated with merging galaxies (Zepf et al. 1999; Zhang & Fall 1999; Ashman & Zepf 2001; Cen 2001; Larsen et al. 2001). The great age and low metallicity of globular cluster systems indicates that they should be present at very high redshifts and predate the bulk of their eventual host galaxies’ stars.

The exciting prospect is that direct studies of globular cluster formation and evolution will soon become possible. The next generation of optical-infrared telescopes on the ground and in space will have the capability to detect objects at the nanojansky level. An estimate of the faint number counts in the optical was undertaken for the Hubble Space Telescope (HST; van den Bergh 1979), but we concentrate on the IR where the redshift and rise in numbers is much more dramatic. In the 2–5 $\mu$m bands, the combination of large k-corrections and substantial stellar brightening raises the fluxes from high-redshift clusters into the range of 29–32 AB mag. These nanojansky flux levels are within the capabilities expected of future telescopes.

Today’s globular clusters are likely the survivors of a larger population present at the various times of formation (Fall & Rees 1977; Fall & Zhang 2001). If their comoving density increases by an order of magnitude over those at low redshift, then the globular clusters are likely to appear with numbers at a given flux level that are comparable to subgalactic-mass dark matter halos, which are the sites of the “first stars” (Couchman & Rees 1986; Haiman & Loeb 1997; Haiman, Abel, & Madau 2001).

This paper calculates the magnitude-limited distribution of the expected numbers, $n(m)$, the redshift distribution, $n(z|m)$, and estimates the angular clustering properties of the globular cluster population relative to their host galaxies. The predictions are made for filter passbands sufficiently red that Ly$\alpha$ trough absorption will not normally be an issue. In the next section, we describe the calculation of the comoving number density of globular clusters (GC) as a function of redshift for different evolutionary assumptions. In §3, we present the results of the number calculations. Section 4 considers the apparent sky clustering of the distant GC. We conclude with a discussion of the opportunities and complications that this population presents. The calculations are presented in a cosmology for which $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. AN EVOLVING GLOBULAR CLUSTER LUMINOSITY FUNCTION

The expected sky density of GCs at magnitude $m$ and redshift $z$ depends on the product of the cosmological volume element and their luminosity function, $\phi_{GC}(L, z)$, integrated with the volume element along the line of sight. The luminosity function has three sources of evolution. First, it is generally accepted that galactic tidal fields and stellar dynamical “shocks” erode a more numerous high redshift GC population into the remnant population we see today. We use the results of a relatively secure theoretical analysis of the evolution of the population but also show results for a nonevolving distribution. Second, as the stellar population becomes younger with increasing redshift, its spectral energy distribution changes. Third, the GCs form at some high, but as yet poorly determined, redshift. Our approach to each of these evolutionary terms, along with the normal-
ization to the present day globular cluster population, is discussed in the following section.

2.1. An Evolving Mass Distribution

Recently Fall & Zhang (2001, hereafter FZ) have discussed a generalized dynamical model for the evolution of the mass distribution of GCs. They find that within 1–2 Gyr of origin, a wide range of initial GC mass distribution assumes a characteristic form which then evolves in a nearly self-similar way. At small mass, all clusters (in the same tidal field) go to zero mass at the same rate due to two-body relaxation-driven evaporation. At high mass, gravitational shocks impose a characteristic maximum mass above which there is a rapid cutoff of numbers. The continual depletion of GCs implies that over a Hubble time, about 10% of the initial cluster population survives, under the assumptions that the system is not replenished and that the galactic potential does not change. FZ have kindly made their model predictions available for use in this paper. Specifically, we use the differential number of GCs at mass \( M \) at time \( t \), \( n_{\text{GC}}(M, t) \text{d}M \), which FZ present in their Figure 3.

It should be noted that the FZ model predicts the mass of the peak. To test this aspect of the models, FZ have put the Milky Way globular clusters on a mass scale using \( M/L_V = 3 \), as is appropriate for an old, metal-poor stellar population. The agreement between model and observation is impressively good. The extensive testing of FZ shows that the results should not change much with galaxy mass or galaxy type.

The FZ model results are specified at times of 0.01, 1.5, 3, 6, and 12 Gyr. We use a double spline function in the variables \( M \) and \( \log t \) to interpolate to other times. We extrapolate slightly beyond their 12 Gyr model to the 13.4 Gyr age of our cosmology. The minimum age of their models is 0.01 Gyr, where the formation distribution is close to a power law in mass. We will show the sensitivity of our results to the GC number evolution.

2.2. The Redshift-Dependent Luminosity Function

We require the redshift-dependent globular cluster luminosity function, \( \phi_{\text{GC}}(L_{\lambda}, z) \), where \( L_{\lambda} \) is the observed luminosity in some filter band centered around \( \lambda \). The conversion from \( n_{\text{GC}}(M) \) to \( \phi_{\text{GC}}(L) \) is made using a spectral synthesis model that gives the entire spectral energy distribution, \( F_{\lambda} \), as a function of model age for given metallicity and star formation history. We use the PEGASE.2 code (Fioc & Rocca-Volmerange 1997) to calculate \( \xi_{\lambda} \), the observed frame luminosity per unit mass in the filter band \( \lambda \),

\[
\xi_{\lambda} = \int_0^\infty T(\lambda) F_{\lambda}(1+z) \lambda \, d\lambda \frac{d\lambda}{(1+z)^{\lambda} d\lambda},
\]

where \( F_{\lambda}(1+z) \lambda/(1+z) \) is the model’s mass-normalized absolute flux in the observed frame and \( T(\lambda) \) is the filter transmission function. Noting that the photon redshift and the time dilation are included in equation (1), an object of mass \( M \) gives an observed flux in the \( \lambda \) filter of

\[
f_{\lambda} = \frac{M \xi_{\lambda}}{4\pi r(z)^2},
\]

where \( r(z) \) is the comoving distance in the adopted cosmology. The observed flux is converted to magnitudes using the definition \( m_{\lambda} = -2.5 \log_{10}(f_{\lambda}) + C \), where \( C \) is 31.4 AB magnitudes at 1 nJy.

2.3. Normalizing the Luminosity Function

The luminosity functions of the GC systems of the Milky Way and more than 50 nearby galaxies have been studied (Harris 1991, 1996). A single galaxy’s GC luminosity function is conventionally described as a Gaussian (in absolute magnitude, hence a lognormal distribution in luminosity) centered at \( \langle M_V \rangle = -7.27 + 5 \log_{10}(H_0/75) \) mag with a dispersion of about 1.2 mag. Although a more complex function, the FZ mass model appears to describe the data at least as well as a Gaussian. Moreover, it is based on a dynamical theory that allows its history to be predicted. To use the FZ function in our calculation, we need to fix the volume normalization, and we will also introduce a small shift in the \( M/L \) value.

2.3.1. Mass-Luminosity Normalization

The mass normalization of the FZ models is determined by the dynamics of the GCs within the model galaxy. Although fairly insensitive to variations in the potential, the mass function does shift slightly, depending on the specific galactic potential. Here we use the luminosity function typical of a mix of galaxies. We adopt the functional form of the FZ mass function and could adopt their \( M/L_V = 3 \) value; however, we prefer to make a small adjustment to provide an alternate match to the observational data. The FZ mass function is a power law on the low-mass side and much steeper than a Gaussian on the high-mass side. Here we chose an \( M/L_V \) value that brings the mean luminosities of the FZ distribution to the mean of the Gaussian fits. A numerical integration finds that \( M_V = -7.27 \) mag should be identified as \( \log M/M_\odot = 5.36 \), which implies an \( M/L_V = 3.3 M_\odot/L_\odot \). This small \( M/L \) change is well within the uncertainty of stellar population modeling. In particular, \( M/L_V = 2.1 M_\odot/L_\odot \) for the \( Z = 0.1 \) solar PEGASE models we compute at an age of 13.4 Gyr. Our normalization effectively raises the \( M/L \) values of the PEGASE models by a multiplicative factor of 1.57.

The \( V \)-band luminosity is widely used to describe low-redshift clusters. However, it is beneficial for the accuracy of our main application to high-redshift galaxies to use \( K \)-band luminosities. Furthermore, the GC population is most closely connected to the old stellar population, which is most accurately measured at low redshift by \( K \)-band luminosities. The conversion from \( V \) to \( K \) must use the IR colors of a population with a metal abundance of about 1/10 solar, \( V-K = 2.93 + 0.5 Z/Z_\odot \) mag (Aaronson et al. 1978). The \( Z = 0.1 Z_\odot \) PEGASE models find \( V-K = 2.4 \) mag at 13.4 Gyr, which is in essentially exact agreement with the observational relation. Using this color, we find that the mean peak \( K \)-band luminosity for GCs is \( \langle M_K \rangle = -9.70 + 3 \log_{10}(H_0/75) \) mag. This value is converted to the flux-based AB magnitude system with the addition of \( AB(K) = r + 1.88 \) mag.

2.3.2. Number Density Normalization

The mean comoving density of GCs for a single galaxy is modeled as being directly proportional to its luminosity (Harris & van den Bergh 1981; Harris 1991).

\[
S_N = N_i 10^{-0.4(M_i+15)},
\]
where $M_V$ is the galaxy’s absolute magnitude in the $V$ band and $N_t$ is the total number in a Gaussian luminosity function. The $S_N$ relation has significant variations with Hubble type and possibly environment but appears to be accurate in the mean (Harris 1991). Since GCs are most clearly associated with old stellar light, it is natural to use a $K$-band luminosity function, in which case

$$S_N = N_t 10^{-0.4(M_K + 17.9)},$$

where a galaxy with solar metallicity has $V-K \simeq 2.9$ mag (Aaronson et al. 1978). Adopting the Gardner et al. (1997) luminosity function (for our purposes, similar to the recent Cole et al. 2001 results) for which $M_v(K) = -23.1$ mag, we find that in the $K$ band, the number of globular clusters around a galaxy rises linearly with luminosity, i.e.,

$$N_t(L_K) = 120 S_N \frac{L_K}{L_*}.$$  

To convert the normalization from globular cluster per galaxy to a volume normalization, we use the luminosity density of galaxy light in the $K$ band, $j(K)$. The normalizing constant for the GC luminosity function is defined such that the integral over all GC luminosities must be equal to the mean number of GC expected for the mean amount of galaxy light in that volume. That is,

$$\int_0^\infty \phi_{GC}(L, z = 0) \; dL = 120 S_N \frac{j(K)}{L_*}.$$  

For Gardner’s (1997) $\alpha = -1$ Schechter luminosity function fit $j(K) = \phi_*(K)L_*(K)$, where $\phi_*(K) = 0.0166 \; h^{-3} \; \text{Mpc}^{-3}$. Note that the dependence on $L_*(K)$ cancels in equation (6). Then the comoving volume density in GCs is $n_{GC}(0) = 2.0 \; h^{-3} \; S_N \; \text{Mpc}^{-3}$, where $h = H_0/100$. We adopt $S_N = 2$ as a reasonable and somewhat conservative value, given that the bulk of the $K$ light emerges from relatively luminous early-type galaxies. Figure 4 and Table 3 of Harris (1991) might suggest a value of about 3 for the early-type galaxies, with evidence that strongly clustered early-type galaxies have higher $S_N$. Of course, the origin of these effects may well be directly visible in the future. The outcome is that our complete GC luminosity function is

$$\phi_{GC}(L, z) \; dL = n_{GC}(0)n_{GC}[L_*/f_*(t), t(z)] \; dL.$$  

The redshift distribution per unit of sky area of GC at a given flux level is simply

$$n(z|f_*) \; d \ln f_*= \int_0^\infty \phi_{GC}[4\pi r^2(z)f_*/z] \; \frac{dV}{dz} \; dz \; d \ln f_*,$$  

where $dV/dz$ is the volume element within the model cosmology. Integrating over the redshift distribution gives the number-magnitude relation. In practice, these calculations are done using magnitudes rather than fluxes.

### 3. COUNTS AND DISTRIBUTIONS

With the modeling apparatus in hand, we first pause to show the low redshift $n(z)$ at $m_R(AB) = 25, 26, 27, \text{and } 28$ mag in Figure 1. The total sky densities of the FZ model at these depths are $87, 321, 1260, \text{and } 4840 \; \text{deg}^{-2} \; \text{per mag}$, respectively. These GCs will be clearly associated with relatively bright galaxies, typically about $m_R(AB) = 13-17$ mag, with the redshift distributions shown.

#### 3.1. Number-Redshift Distributions

Precisely how globular clusters form is, at this time, unknown. Part of the point of this paper is that the plausible formation redshifts for the bulk of GCs will shortly come within reach of telescopes. To try to bracket the situation, we examine a number of somewhat extreme alternative models and look at the effects of coordinated bursts in a galaxy. To examine the importance of luminosity spikes at the time of formation, we use (arbitrarily, for the purpose of illustration) 10 bursts of star formation of duration 10 Myr spread over the 0 to 1 Gyr time interval. The formation age of all of the GC is put at 0.5 Gyr. The results are shown in Figure 2. Such bursts would affect the counts in an area small enough that only a few dozen actively GC forming galaxies were present.

In Figure 3, we use the same set of 10 star formation bursts but shifted in time to the 1 to 2 Gyr time interval, with a uniform formation age of 1 Gyr. Clearly, the bursts of star formation produce spikes in the redshift distribution, but those effects quickly die away. It could be that the earliest phases of globular cluster formation are cloaked in dust which later disperses, following an age-extinction relation (Shapley et al. 2001). In that case, the high-luminosity peaks will be a briefly obscured phase in the life of GCs. However, the figures show that if those short-lived bright spikes are removed, neither the counts nor redshift distribution will be greatly altered.

The difference between the no-evolution and FZ density evolution models are small at redshifts below about 3, under the assumption that most globular clusters were formed at redshifts greater than 3. The differences would be much larger if significant globular cluster formation continued to
The number-magnitude relation is shown in Figure 4 in the $V$, $R$, $J$, $K$, $L$, and $M$ bands (spanning roughly 0.5 to 5 μm) for our model with 10 bursts of 10% of the mass, spread between 0 and 1 Gyr. There are two effects. At low redshift, the counts rise with increasing magnitude at a rate governed by the volume element, enhanced by $k$-corrections in an old, low-metallicity population. Although not shown, at 1 nJy in the $V$ band, the $n(z)$ peaks at about redshift 0.3. At 1 nJy in the $R$ band, $n(z)$ peaks at about redshift 0.5, with a few of the actively star-forming $z = 5$ clusters in formation being visible. Clearly, deep optical band observations are not the ideal way to probe the formation epoch. The character of the redshift distribution changes in the infrared bands as the peak of the spectrum is redshifted into them. The combination of $k$-correction and luminosity evolution causes the counts in the redder bands to rapidly climb to several million deg$^{-2}$. As Figure 4 shows, the counts are steeper than Euclidean near 30 AB mag in the IR bands.

The predicted counts for a wide range of model star formation histories are shown in Figure 5. We display the $L$ band counts for models having 10 bursts of 10% of the final-mass star formation extending over 10 Myr in the 0–1 Gyr interval (triangles), the 1–2 Gyr interval (diamonds), and exponential models with $\tau = 1$ (pentagons), 2 (heptagons), and 4 Gyr (hexagons) for both evolving and nonevolving mass function. The number-magnitude relation shows substantial model dependencies beginning at about 1 nJy ($m_{AB} = 31.4$ mag). However, the result that the $L$ band counts will be around $10^8$ mag$^{-1}$ deg$^{-2}$ at 0.2 nJy is reasonably robust. It does not depend a lot on star formation, internal dust shrouding in the early phases, and is not unduly sensitive to the exact amount of GC density evolu-

Fig. 2.—Redshift distribution in the $L$ band (around 3.5 microns) where the GCs form over the time range of 0–1 Gyr in 10 bursts of 10 Myr. Solid line: density evolution model. Dotted line: no-density evolution model. Curves are presented for 0.2, 0.5, 1, 2, 4, 10, and 20 nJy, equivalent to 33.15, 32.15, 31.4, 30.65, 29.9, 28.9, and 28.15 AB mag, respectively.

Fig. 3.—Redshift distribution in the $L$ band for 10 bursts of 10 Myr of GC formation over the 1 to 2 Gyr time interval. Line types are as in Fig. 2. The same magnitude limits as in Fig 2 are used.

Fig. 4.—Number per magnitude per square degree as a function of limiting AB magnitude for the $V$ (triangles), $R$ (diamonds), $J$ (pentagons), $K$ (hexagons), $L$ (heptagons), and $M$ (octagons) bands. The solid lines are evolving density models and the dotted are fixed comoving density models. [See the electronic edition of the Journal for a color version of this figure.]
tion. The biggest potential overprediction of numbers is if GCs initially form in dusty disk environments which makes them hard to detect. As long as the clusters become visible within about 2 Gyr of formation, the numbers predicted here should be fairly accurate. The basic prediction that the sky density becomes about $10^7$ deg$^{-2}$ around 1 nJy is difficult to escape, given the assumptions about globular cluster origins, evolution, and visibility made in this paper.

4. ANGULAR CLUSTERING

Globular clusters are strongly concentrated around their host galaxies. At the very low flux levels we are investigating here, it is natural to ask to what degree this clustering will remain evident and whether the nonlocal sky will effectively be covered with a nearly uniform distribution of GCs. A prediction of clustering uses the results above but requires additional information about the degree to which galaxies and their GC systems merge into larger and larger units. Furthermore, the host galaxies may not always be visible at the highest redshifts considered here, since galaxies are generally younger and have a much lower surface brightness than GCs. Hence, the following estimates of galaxy-GC cross-correlations will be upper limits, although we do incorporate a model for galaxy merging into our calculations.

The real space cross-correlation of galaxies and GCs can be derived from the average radial profile of GCs in their host galaxies. As shown below, the autocorrelation of galaxies makes no significant contribution at the angles of interest. The FZ calculations find that after approximately $1\to2$ Gyr, the radial distribution converges to a stable, nearly power-law form. An approximate power-law fit to the Milky Way data of Harris (1996) is

$$n(r) = 3 \times 10^2 \left( \frac{r}{10 \text{ kpc}} \right)^{-3.5} \text{kpc}^{-3} \tag{9}$$

If there is a core in the radial distribution, it appears at a radius of order a few kpc where the GCs become superimposed on significant galaxy light and hard to find. The Milky Way is probably somewhat less than $L_\ast$ in luminosity, and its GC system, with a total of $160 \pm 20$ clusters (Harris 1991), has numbers about 2/3, half of the 240 expected at $L_\ast$. To calculate the cross-correlation function with galaxies we need $\delta(r) = [n(r) - n_0]/n_0$, where $n_0$ is the mean density. We normalize these numbers to the volume average for $L_\ast$ galaxies. The mean GC density of $4.0 \ h^{-3}$ Mpc$^{-3}$ we derived above becomes a physical density of $1.2 \times 10^{-9}$ kpc$^{-3}$ for $H_0 = 70$. Consequently, we can re-express equation (9) as the overdensity

$$\delta(r) = 2.5 \times 10^{10} \left( \frac{r}{10 \text{ kpc}} \right)^{-3.5} \tag{10}$$

Converting this to the standard correlation length form and using comoving coordinates ($H_0 = 70$),

$$\xi_{\text{GC}}(x) = \left( \frac{9.4 \text{ Mpc}}{x} \right)^3 \frac{L_h}{L_\ast}, \tag{11}$$

where we have included the luminosity dependence, with $L_h$ being the luminosity of the host galaxy. Note that an alternate description of this correlation length is $6.6 \ h^{-1}$ Mpc. In this calculation, we have assumed that the low-redshift $S$ relationship holds in the earliest phases of the life of a galaxy, which needs to be tested. An overall density normalization change has no effect on the correlations, since the mean field density changes at the same rate, leaving $\delta$ invariant.

GC systems appear to always be associated with more or less virialized galaxies. They are not part of a clustering hierarchy that extends into the linear regime. Therefore, we describe the overdensity distribution as being fixed in physical coordinates. We therefore multiply equation (11) by the correlation function evolution term $(1 + z)^\gamma$. The quantity $\gamma$ is equal to $\gamma - 3$ for fixed overdensity in physical coordinates, as is appropriate here.

Galaxies are assembled over time through the merger process. A simple model for the increase of mass $M$ is $dM/dt = \mathcal{R}(1+z)^\delta$. Approximating $1+z = t_0/t$ (as in an empty universe), this integrates to

$$M(z) = \begin{cases} M_0 - \mathcal{R}(\mathcal{M}t_0)^{-1}(1+z)^{\delta-1}, & \mathcal{M} > 1, \\ M_0 - \mathcal{R}0 \log(1+z), & \mathcal{M} = 1 \end{cases} \tag{12}$$

Note that $M(z)$ goes to zero for finite $z$ for $\mathcal{M} > 1$. Reasonable values are $\mathcal{M} \simeq 1\to3$ and $\mathcal{R}t_0 \simeq 0.2\to0.5$ (Carlberg et al. 2000; Le Fèvre et al. 2000). The resulting redshift-dependent comoving correlation function, $\xi_{\text{GC}}(x,z)$, is

$$\left[ \frac{r_0(z)}{x} \right]^\gamma \left[ \frac{r_0(z)}{x(z)} \right]^\gamma \frac{M(z)}{M_0}. \tag{13}$$

The angular correlation function is simply related to the volume correlation through a projection over redshift,

$$\omega(\theta) = A(\gamma)\theta^\gamma N^{-2} \int n^2(z) \left[ \frac{r_0(z)}{x} \right]\gamma \frac{H(z)}{c} dz, \tag{14}$$
where \[ N = \int f(z) \, dz, \quad A(\gamma) = \Gamma(1/2) \Gamma[(\gamma - 1)/2] \Gamma(\gamma/2), \]
and \[ H(z) = H_0[\Omega_M(1 + z)^3 + \Omega_R(1 + z)^3 + \Omega_\Lambda]^{1/2}, \]
with \[ \Omega_M + \Omega_R + \Omega_\Lambda = 1. \]

We express the results as an angular correlation \[ \omega(\theta) = (\theta_0/\theta)^{-1} \].
We evaluate the integral using the L band \[ n(z) \] at \f 1 \f nJy. For our \( r_{00} = 6.6 \, h^{-1} \, \text{Mpc} \), \( \gamma = 3.5 \), and \( \epsilon = 0.5 \), we find \( \theta_0 = 22'' \) and \( 18'' \), with \( \theta_0 = 0.5 \) for \( h = 1 \) and \( 2 \), respectively, and \( 21'' \) and \( 17'' \) for \( h = 0.3 \) for the same \( \omega \). Correlation angles of \( 20'' \) correspond to physical distances of about 100 kpc around redshift 3. Therefore, the bulk of the GCs will be clearly associated with their host galaxies. The galaxies, if they exist and are not obscured, will be some \( \sim 10 \) to \( 12 \) mag brighter than the GCs, depending on the relative roles of merging and luminosity evolution. At \( K_{AB} \approx 20 \) to \( 22 \) mag, galaxies have mean sky separations of \( \sim 20'' \) to \( 40'' \), so the sky will be effectively covered, albeit with a concentration toward galaxies or the still-dark halos that will become the sites of galaxies.

The GC-galaxy cross-correlation calculation ignores the contribution of galaxy-galaxy clustering. The same of calculation shows that the much shallower \( \gamma = 1.8 \) of galaxy clustering the autocorrelation angle is about \( 2'' \) for \( r_{00} = 5 \, h^{-1} \, \text{Mpc} \). For the GCs, their steep cross-correlation with galaxies allows them to rapidly climb out of the projected distribution, which does not occur for the galaxy-galaxy correlation. The galaxy-galaxy contribution will only be visible at about an arcminute, where the projected clustering distribution, which does not occur for the galaxy-galaxy correlation. The galaxy-galaxy contribution will only be visible at about an arcminute, where the projected clustering amplitude is only \( \sim 0.03 \). At angles less than \( 20'' \), the contribution is less than 10%, given our modeling for clustering. Of course, globular cluster formation during merging is a special case.

5. DISCUSSION AND CONCLUSIONS

Globular clusters are, in the main, very old objects, likely formed in the first quartile of the age of the universe, implying strong luminosity evolution at high redshift. The combination of k-corrections and luminosity evolution put the bulk of their energy in the 3–5 \( \mu \text{m} \) bands. For a fairly wide range of density and luminosity evolution models, there should be approximately \( 10^7 \) GC deg\(^{-2} \) mag\(^{-1} \), with a continuing steep rise in counts. In the optical bands, the counts rise slowly, with few GC appearing beyond redshift 1.

Source confusion noise in flux and position measurements increases in proportion to the density of sources relative to the beam density, \( \ln(2/\pi)(D/\lambda)^2 \) (Scheuer 1974; Condon 1974). The problems associated with confusion begin to arise when the source density is about \( \sim 5\% \) of the beam density. Moreover, the strong clustering of GCs toward galaxies will create enhanced confusion in the neighborhood of galaxies. A diffraction-limited 6 m telescope operating at 4 \( \mu \text{m} \) will have one source per beam (severe confusion) at a sky density \( 1.5 \times 10^3 \, \text{deg}^{-2} \). For the relatively steep source counts found here and the high confidence detections that would be of interest to photometric redshift estimation techniques, the source density below about 1 nJy presents an issue to be carefully approached. In detail, this problem could be more quantitatively addressed with simulated observations using the predicted counts. In a future paper, we will also consider a more detailed model that incorporates dust and emission line nebula effects and a number of potential astrophysical complications.

The large density of high-redshift GCs is both an opportunity and a challenge. In as much as GCs are key indicators of how the extended low-metallicity stellar halos of galaxies came into being, observations at nJy flux levels will directly probe their origins. On the other hand, the sky densities and flux levels are similar to those predicted for zero-metallicity “first light” objects. It will require some care to distinguish a young cluster of fairly normal stars with strong ionizing radiation from the unusual zero-metallicity stars that are the first luminous objects. It will be fascinating to understand the relationship between these two “early light” populations.

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REFERENCES

Aaronson, M., Cohen, J. G., Mould, J., & Malkan, M. 1978, ApJ, 223, 824
Ashman, K. M., & Zepf, S. E. 2001, AJ, 122, 1888
Carlberg, R. G., et al. 2000, ApJ, 532, L1
Cen, R. 2001, ApJ, 560, 592
Cole, S., et al. 2001, MNRAS, 326, 255
Condon, J. J. 1974, ApJ, 188, 279
Côté, P., Marzke, R. O., & West, M. J. 1998, ApJ, 501, 554
Couchman, H. M. P., & Rees, M. J. 1986, MNRAS, 221, 53
Fall, S. M., & Rees, M. J. 1977, MNRAS, 181, 73P
Fall, S. M., & Zhang, Q. 2001, ApJ, 561, 751
Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950
Gardner, J. P., Sharples, R. M., Frenk, C. S., & Carrasco, B. E. 1997, ApJ, 480, 199
Haiman, Z., Abel, T., & Madau, P. 2001, ApJ, 551, 599
Haiman, Z., & Loeb, A. 1997, ApJ, 483, 21
Harris, W. E. 1991, ARA&A, 29, 543
Harris, W. E. 1996, AJ, 112, 1487
Harris, W. E., & van den Bergh, S. 1981, AJ, 86, 1627
Larsen, S., Brodie, J. P., Elmegreen, B. G., Efremov, Y. N., Hodge, P. W., & Richtler, T. 2001, ApJ, 556, 801
Le Fèvre, O., et al. 2000, MNRAS, 311, 565
Scheuer, P. A. G. 1974, MNRAS, 167, 329
Searle, L., & Zinn, R. 1978, ApJ, 225, 357
Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95
VandenBerg, D. A. 2000, ApJS, 129, 315
van den Bergh, S. 1979, in IAU Colloq. 54, Scientific Research with the Space Telescope, ed. M. S. Longair & J. W. Warner (Washington: NASA), 151
Zepf, S. E., Ashman, K. M., English, J., Freeman, K. C., & Sharples, R. M. 1999, AJ, 118, 752
Zhang, Q., & Fall, S. M. 1999, ApJ, 527, L81