1. INTRODUCTION

One of the remarkable observational facts about the stellar content of galaxies is the ubiquity of globular star clusters. These clusters can be found in almost all but the least massive galaxies. Generally globular clusters come in two major families of comparable mass: metal-poor, old blue clusters and metal-richer, younger, red clusters. A comprehensive review of globular clusters can be found in almost all but the least massive galaxies. Generally globular clusters come in two major families of clusters can be found in almost all but the least massive galaxies. Generally globular clusters come in two major families of comparable mass: metal-poor, old blue clusters and metal-richer, younger, red clusters. A comprehensive review of globular cluster systems is given by Harris (2001). Below we present quantitative arguments for the formation of clusters during mergers and use the observations to obtain the key parameters of the model. This formation picture leads naturally to a phenomenological model for galaxy evolution. Combined with a simple chemical evolution model, comparisons with recent data for Galactic halo stars are made.

2. MERGER-INDUCED GLOBULAR CLUSTER FORMATION

The possibility of forming globular clusters from collisions between gas-rich bodies was considered by Gunn (1980) and independently by McCrea (1982). We revive and extend the Gunn and McCrea analysis here.

2.1. The Model

Within each of the two equal mass interacting galaxies, consider an undisturbed column of gas of length \( l \), cross-sectional area \( A \), and density \( \rho_o \), meeting its counterpart with relative velocity \( 2V \) (see Figure 1). During the collision, the gas is compressed to column length \( \lambda \) and density \( \rho \). The shocked gas is assumed to cool to \( T \sim 10^4 \) degrees. This assumption will be justified later—sufficient to say that the cooling time within the compressed volume \( (\tau_{\text{coll}}) \) must be shorter than the collision time \( (\tau_{\text{coll}} \sim 1/V) \) for the assumption to be valid. By conservation of mass and for simplicity, assuming \( A \) to remain constant,

\[
2\rho_o l A = \rho \lambda A
\]

equivalently in terms of the column density

\[
2\Sigma_o = \Sigma
\]

and

\[
\frac{\rho}{\rho_o} = \frac{2f}{\lambda}
\]

with the relative velocity being \( 2V \), the relation between \( \rho_o \) and \( \rho \) becomes (e.g., Spitzer (1978), Equation (10-24))

\[
\rho_o A V^2 \simeq \rho \left( \frac{kT}{\mu m_H} \right)
\]

so that

\[
\frac{\rho}{\rho_o} \simeq 0.048V^2/(T_4/\mu),
\]

where the bracketed quantity in Equation (4) represents the square of the sound speed, and in Equation (5) the unit of \( V \) is \( \text{km s}^{-1} \), \( T_4 \) is the temperature in units of \( 10^4 \) degrees, and \( \mu \) is the mean molecular weight of the shocked gas. The quantity \( (T_4/\mu) \) occurs frequently in the expressions below. With \( \mu = 0.59 \), a typical value for this quantity is \( \sim 1.7 \). Combining Equations (3) and (5),

\[
\frac{1}{\lambda} \simeq 0.024V^2/(T_4/\mu).
\]

The Jeans length, \( \lambda_J \) is

\[
\lambda_J = \left( \frac{\pi k T}{\mu m_H G \rho} \right)^{1/2} \simeq \frac{246}{\rho^{1/2}(T_4/\mu)^{1/2}} \text{pc},
\]

with \( \rho \) in units of \( M_\odot \text{ pc}^{-3} \). Equating \( \lambda \) with \( \lambda_J \) eliminating \( \rho \),

\[
\lambda = \lambda_J = \frac{6.05 \times 10^4}{2\Sigma_o}(T_4/\mu) \text{pc}.
\]

Finally, the Jeans mass is given by

\[
M_J = \rho \lambda^3 = 2\Sigma_o \lambda^2 = 6.05 \times 10^4 \lambda(T_4/\mu) M_\odot.
\]

If the cooling time of this gravitationally unstable mass, \( \tau_{\text{cool}} \), is shorter than the free-fall time \( (\tau_{ff}) \), then fragmentation can occur. The cooling function \( A(Z) \) which when multiplied by the square of the particle density of hydrogen gives the cooling rate per unit volume, falls precipitously from a metallicity-independent peak near \( T \sim T_4 \) to a metallicity-dependent plateau below (e.g., Dalgarno & McCray (1972)). The cooling rate from heavy elements alone at \( T_4 \sim 0.9 \) is \( \gtrsim 4 \times 10^{-26}(Z/Z_\odot)n_H^2 \) \( \text{cm}^3 \text{s}^{-1} \) (e.g., Fall & Rees (1985, Section 4, p. 22)). From \( \tau_{\text{cool}} \sim 1.5n_kT/(\Lambda n_H^2) \) and with the density in \( M_\odot \text{ pc}^{-3} \), the cooling timescale becomes \( \sim 6.96 \times 10^4(Z/Z_\odot)^{-1}(T_4/\mu)/\rho \text{ yr} \). Similarly, \( \tau_{ff} = (32G\rho/3\pi)^{-1/2} \) reduces to \( \sim 8.08 \times 10^6/\rho^{1/2} \text{ yr} \).
Finally, from Equations (3) and (4) one can write \( \tau_{\text{coll}} = \tau_s \eta \), where \( \tau_c = \lambda / c_s \sim 1.07 \times 10^5 \lambda (T_d / \mu)^{-1/2} \) yr, \( c_s \) is the sound speed, \( \lambda \) is in pc, and \( \eta \) is the Mach number \( (2V_0 / c_s) \) and is \( \gg 1 \). Eliminating the density using Equation (7), the relevant timescale ratios become

\[
\frac{\tau_{\text{cool}}}{\tau_{\text{coll}}} \sim \frac{\tau_{\text{cool}}}{\tau_s} \sim 1.07 \times 10^{-5} \lambda (Z / Z_\odot)^{-1} (T_d / \mu)^{1/2} \quad (10)
\]

and

\[
\frac{\tau_{\text{cool}}}{\tau_{\text{coll}}} \sim 3.5 \times 10^{-5} \lambda (Z / Z_\odot)^{-1} (T_d / \mu)^{1/2}. \quad (11)
\]

As will be shown in the next section, the observationally determined value of \( \lambda \) is such that both of these ratios are less than unity. Hence our assumption that the shock is isothermal is justified. We are also assuming that the temperature of the gas remains constant at the maximum of the cooling function near \( T_d \sim 1 \) until the mass becomes Jeans-unstable. Further, one can expect fragmentation to occur when the gravitationally unstable cloud begins to collapse as long as \( Z / Z_\odot \) is not much less than \( \sim 0.01 \). This is also the threshold metallicity below which globular clusters are not observed.

Assuming that stars are eventually formed, another consideration is the efficiency \( \eta \) with which gas is turned into stars. This is not well known at present, so for the later discussion we assume this quantity to be \( \eta \sim \Omega_{\text{star}} / \Omega_{\text{baryon}} \sim 0.07 \). This ratio represents the global stellar mass density divided by the total baryonic mass. A further question then arises because the mass loss associated with star formation and evolution can lead to the dissolution of any cluster of stars formed. This problem has been investigated by Geyer & Burkert (2001) and more recently in their discussion of the globular cluster mass function by Parmentier & Gilmore (2007). Unfortunately, the observations which would allow an empirical estimate of the bound to unbound stellar ratio are not yet available, so that more sophisticated modeling is required to answer this question in the context here. To proceed, we shall consider \( \eta \) to set an upper limit to the mass of a bound cluster of stars formed.

A final point to note is that in this model the gas is concentrated by collision and the co-orbiting stars and dark matter will at least initially be unaffected by this process. Hence we do not expect the resulting globular clusters to contain a significant amount of dark matter.

![Figure 1](image1.png)  
**Figure 1.** Two gas columns approach one another with relative velocity \( 2V \) and collide, reducing the column length from \( l \) to \( \lambda \) and increasing the density from \( \rho_0 \) to \( \rho \).

![Figure 2](image2.png)  
**Figure 2.** Twice the log of the radial extent of the neutral hydrogen gas \( r_{HI} \) vs. the log of \( 1.3 \times M_{HI} \). The solid line has a slope of unity. The solid points are from Broeils & Rhee (1997), while the open circles are from the work of Begum et al. (2008a, 2008b). The units of \( r_{HI} \) and \( M_{HI} \) are pc and \( M_\odot \), respectively.

### 2.2. Relating the Model to the Observations

It is clear from the above discussion that the crucial quantity to determine is \( \lambda \), while the principal variables are a characteristic length \( l \), and a characteristic velocity \( V \). Given that the available observational parameters of the dominant gaseous component of galaxies are the radius of the \( H I \) disk, \( r_{HI} \), the mass of the \( H I \) gas, \( M_{HI} \), and the peak rotational velocity of the \( H I \), \( V_{\text{rot}} \), we begin by identifying \( l \) with \( r_{HI} \) and \( V \) with \( V_{\text{rot}} \). By identifying \( V \) with \( V_{\text{rot}} \), we are considering mainly edge-on collisions. While the mass does not directly enter into the discussion above, correlations between it and the other variables lead to interesting results. The mass parameter actually used here is \( 1.3 M_{HI} \) in order to allow for the contribution of helium. Throughout the rest of this work, the symbol \( M_{HI} \) will generally represent both the hydrogen and helium gas content.

The data discussed here come from two sources. The first for relatively bright galaxies are from Broeils and Rhee (1997) and the second for dwarf irregular galaxies are from Begum et al. (2008a, 2008b). In order to intercompare both data sets, a correction to both \( r \) and \( M \) was made for the small difference in the assumed Hubble constant. In addition, because the \( H I \) radii were measured at a different limiting surface brightness, a correction of +0.178 in \( \log r \) was applied to the Broeils and Rhee data. This was determined by jointly correlating the radii and the masses and finding the minimum dispersion. This correction is well within the uncertainties quoted by Begum et al. in their discussion of this problem. Figure 2 shows the resulting relation between \( 2 \log r_{HI} \) and \( \log M_{HI} \). The solid line has a slope of 1,
while a least-squares fit for this slope gives 0.994 ± 0.012 for all 137 galaxies. The logarithmic intercept (log $M - 2 log r$) is 0.846 ± 0.132. Hence in agreement with Begum et al., the H I surface density appears to be remarkably constant over nearly 5 orders of magnitude in mass. Note that this face-on surface density is not to be confused with $\Sigma_o$ above where it represents the column density.

Equation (6) above implies that if $\lambda$ is a constant, then a relation between 2 log $V$ and log $r$ should determine its value. Figure 3 shows such a plot. Possibly, a more familiar way to look at this relation is to eliminate $r$ by using the relationship established in Figure 2. Since $r \propto M^{1/2}$, Equation (6) implies $M \propto V_{rot}^4$, i.e., an H I Tully–Fisher relation is predicted. This is shown in Figure 4. The solid line in both Figures 3 and 4 has a slope of 1. Least-squares fits to the data with $V_{rot} > 41.7 \text{ km s}^{-1}$ (i.e., above the dashed lines) give 0.978 ± 0.078 in Figure 3 and 0.989 ± 0.089 in Figure 4. Both regressions included 109 galaxies. The logarithmic intercepts are (log $r - 2 \log V_{rot}$) $= 0.168 \pm 0.250$ and (log $M - 4 \log V$) $= 1.18 \pm 0.515$. Solving for $\lambda$ from each one obtains $\lambda = 61.3 \pm 35.3 (T_d/\mu)$ pc and $\lambda = 61.4 \pm 36.3 (T_d/\mu)$ pc, respectively. Although the uncertainties are large, the numerical difference is small given the tight correlation seen in Figure 2. Given this value of $\lambda$, the timescale arguments above are justified. It should be noted, however, that the condition for fragmentation will be violated for values of $Z/Z_\odot$ not much below 0.01. This provides a natural explanation for the observed abundance threshold of this order below which globular clusters are not observed, a point also made by Gunn (1980).

Returning to Equation (9), the Jeans mass becomes $M_J = 3.7 \pm 2.1 \times 10^8 (T_d/\mu)^2 M_\odot$. Allowing for a gas to star formation efficiency of $\eta \sim 0.07$ results in a predicted globular cluster mass upper limit of $M_{GC} \sim 2.6 \pm 1.5 \times 10^5 (T_d/\mu)^2 M_\odot$.

Begum et al. (2008a) have also noted that the dwarf irregular galaxies with the lowest rotational velocities (i.e., those below the dashed line in Figures 3 and 4) lie below the extrapolated baryonic Tully–Fisher relation. If all of the galaxies are rotationally supported, then $V_{rot}^2 = \alpha GM_{HI}/r_{HI}$, where $\alpha$ is the ratio of the total mass enclosed within $r_{HI}$ to the gas mass. Given the relatively tight relation in Figure 2, the increased scatter in Figures 3 and 4 can be understood as due to variations in this ratio. In order to account for the data below the dashed lines, either the gas is not fully rotationally supported or there is a systematic shift in the value of $\alpha$ toward a lower value in spite of the tight correlation between the H I radius and the mass in Figure 2.

Suppose that the galaxies below the dashed lines are indeed relatively gas-rich (i.e., low $\alpha$). These objects could then be more representative of the universe as it was 13 Gyr ago and the protogalactic clumps from which the present galaxies were assembled. Fitting lines of slope unity through these 28 points in Figures 3 and 4 then yields values of $\lambda$ of 310 ± 272($T_d/\mu$) pc and 307 ± 271($T_d/\mu$) pc, respectively, i.e., a factor of ~ 5 higher than from the more massive galaxies, and hence a Jeans mass higher by the same amount. In order to recover
the observed globular cluster masses, one would need to invoke a star formation efficiency smaller by the same amount. In any event because the clusters are old and relatively metal-poor, it will be argued below that these clusters were formed from the mergers of dwarf irregular galaxies, whether those below the dashed lines in Figures 3 and 4 or at the low-mass end of those above.

At the beginning of this discussion, we chose to identify the $l$ and $V$ of the model with $r_{\text{HI}}$ and $V_{\text{rot}}$ of the gas-rich galaxies. The choice of $V_{\text{rot}}$ would seem to be natural, since during the interaction between two counter-rotating galaxies, the undisturbed gas is rotationally supported. The choice of $r_{\text{HI}}$ for $l$ then leads to a "reasonable" mass for a globular cluster. A further consistency check comes from the model prediction that the column density of gas ($\Sigma_o = \rho_o l$) must be a constant and equal to $\Sigma_o = 3.02 \times 10^3 (T_4/\mu)/\lambda$. With the value of $\lambda$ derived above (assuming $l = r_{\text{HI}}$), $\Sigma_o = 496 \pm 285 M_\odot \text{pc}^{-2}$. This in turn implies a value for the undisturbed particle density varying from $\sim 7$–0.2 gas particles cm$^{-3}$ as the galaxy radius increases from 2.5 to 100 kpc. For a Milky-Way-sized galaxy ($r_{\text{HI}} \sim 25$ kpc), $n_\text{HI} \sim 0.6 \pm 0.4$ cm$^{-3}$ compared to an observed value of $n_\text{HI} = 0.57$ cm$^{-3}$ (Dickey & Lockman 1990).

If a structure in the universe forms hierarchically as is currently believed, i.e., low-mass structures form first and merge to make larger objects, then we expect the oldest clusters to have been formed at the time when the low-mass systems were merging. In fact, genuine globular clusters (both blue and red) are found in many "surviving" dwarf irregular galaxies (e.g., van den Bergh 2006; Georgiev et al. 2008). Generally, as larger structures merge, we expect clusters of similar mass to form but have progressively younger ages and higher metallicities. Today, given the right circumstances, these objects should still be forming and may resemble the super star clusters first observed by Schweizer (1987) in the Antennae galaxies. Conversely, the Galactic building blocks could not have been much more massive than the dwarf irregular galaxies before merging or the red globular cluster backbone would have been younger and more metal-rich than observed.

In the next section, an outline of galaxy formation based on this picture is presented.

3. IMPLICATIONS FOR GALAXY EVOLUTION

We now incorporate the above cluster formation model into an outline for galaxy evolution. The two separate globular cluster families (i.e., the old metal-poor blue ones and the slightly younger metal-rich red ones) are also found in different locations in a galaxy. Unlike the red clusters which are almost exclusively found in the inner regions of galaxy halos, the blue globular clusters can be found in both the inner and outer regions (e.g., Harris 2001). In order to account for these differences, we invoke an anisotropic collapse picture. We imagine that a spiral galaxy forms within a filament of protogalactic clumps of
gas and dark matter. The filament is assumed to collapse first in a direction perpendicular to the filament length and then along its length. Generally, the angular momentum content of a galaxy is distributed, so we expect the low angular momentum building blocks to collide in the first collapse, and in a major burst of star formation form the blue clusters and associated field stars. While the previously formed stars and dark matter will form a more diffuse background, the gas left over after the star formation burst from which the blue globulars and associated field stars form will fall to the center and eventually be available to form the nucleus of the galaxy and contribute to the low angular momentum component of the bulge. The end result is a population of field stars formed prior to the mergers and their associated dark matter halos and postmerger blue globulars, and stars formed as a result of the merging activity but with different kinematics than the prior population. The higher angular momentum building blocks continue to become enriched and slowly spiral in toward the center, at which time they begin colliding with each other and leave behind a diffuse background of stars, dark matter, and any previously formed blue globular clusters. The gas undergoes a second major burst of star formation and red globular cluster formation before the residual gas eventually falls to form the disk. A chemical evolutionary model based on this picture was also able to account for the global star formation history was given in H04. The model parameters are log \( \sigma_p \) = −50, and \( \sim 0.7 \) to estimate the mass of the stars and the clusters. The solid black line (arbitrary normalization) shows the predicted metallicity distribution of stars and a mass of gas with a single metallicity. Now suppose that these truncations occur over a finite range of metallicity dictated by a Gaussian distribution for example. Then we shall end up with a more smoothly truncated stellar distribution and finite spread in the metallicity of the leftover gas which should be almost Gaussian shaped. The end result mimics the result of many zones having undergone truncations (mergers) over a range of metallicity. The model also allows for mass loss to occur at a rate proportional to the star formation rate by defining an effective yield.

Figure 5 is taken from the paper of Ivezic et al. (2008) (bottom right of their Figure 7). The points with error bars show the metallicity distribution of halo stars with height above the plane \( |Z| = 5–7 \) kpc. The blue curve shows the predicted metallicity distribution of the leftover gas after the collisions have taken place. Because the model does not predict either the metallicity distribution or the mass of the stars formed during the mergers, we have assumed that the postmerger stellar and cluster distribution is the same as that of the leftover gas and used a gas to star formation efficiency of \( \sim 0.07 \) to estimate the mass of the stars and the clusters. The solid black line (arbitrary normalization) shows the distribution of metallicity of the stars formed prior to the mergers. It was calculated using exactly the same chemical evolution model given in H04. The model parameters are log \( p_{\text{eff}}/Z_\odot \) = −0.3, log \( Z_c/Z_\odot \) = −1.50, and \( \sigma_{\text{blue}} = 0.32 \). Using the above star formation efficiency, the ratio of the mass of stars formed during the mergers to those formed prior to the collisions is \( \sim 0.8 \). This number will also depend on the value assumed for \( p_{\text{eff}} \). For illustrative purposes here and to minimize parameters, we have kept the effective yield the same as the true yield (i.e., 0.5 \( Z_\odot \)). The stars formed prior to the merger are clearly more metal-poor than the postmerger population and apparently do not show up in the data in Figure 5, although no attempt was made to fit more than one component to the data. These stars are expected to have different kinematic properties, since they would not have been affected in the same way by the collisions which produced the burst of star formation and clusters. In fact, these stars may belong to the second blue halo population which is more metal-poor and with different kinematics identified in a deeper survey by Carollo et al. (2007).

Note that a prediction of this model is that generally the stars enclosed by the blue curve should have the same kinematics and spatial distribution as the blue (halo) globular clusters, since they are assumed to have formed at the same time. Further, these clusters should belong to the “young” halo group of Zinn (1993).

Figure 6 from the top right of Figure 7 of Ivezic et al. shows a similar plot but now with stars from \( |Z| = 1.5–2.0 \) kpc. Here the red curve is the chemical model metallicity prediction assumed for stars and red clusters formed during the second set of collisions. Instead of using a Gaussian to determine the metallicity distribution of the stars/clusters formed during the collisions, we have used an extreme value distribution function which has the shape of an asymmetrical Gaussian, i.e., the function \( f \) of H04 is replaced by

\[
f = \exp(-\exp(-(\log Z_c - \log Z)/w)),
\]

and the Gaussian function in Equation (8) of H04 \( df/d \log Z \) is replaced by the expression

\[
df/d \log Z = \exp(-(\log Z_c - \log Z)/w) \exp(-(\log Z_c - \log Z)/w)/w.
\]

The model parameters are log \( p_{\text{eff}}/Z_\odot \) = −0.3, log \( Z_c/Z_\odot \) = −0.68, and \( w = 0.16 \). This function could have been used for the blue clusters as well, but the fit was marginally better using the Gaussian for them given that only one component was being fitted.

The solid black line (arbitrary normalization) shows the metallicity distribution of all stars formed in the surviving population of building blocks prior to the second major merger phase. This group of stars (called the red spheroid in H04) will be more diffuse, have different kinematics, and will possess a metal-weak tail. The mass ratio between these two components (post to prior) for the parameters assumed above is \( \sim 0.2 \).

Note that any blue clusters that formed prior to the first major merger phase and which remained bound to its lower mass galaxy while avoiding the first mergers will also have the kinematics of the red spheroid population, and hence would be members of the “old” halo component of Zinn (1993). The red clusters should have the same kinematics as the stars under the red curve of Figure 6. The closest analog of a thick-disk population in this model are these same stars.

The main purpose of this discussion is to show that the phenomenological model outlined above is at least qualitatively consistent with the new data and with our picture of globular cluster formation. Further, the general outline for galaxy
evolution described above may help explain additional globular-cluster-related questions. For example, the blue–red cluster phenomenon is also present in elliptical galaxies even though they are morphologically quite different from the gas-rich systems. Could it be that ellipticals formed similarly but at the intersection of more than one filament? The increased frequency of collisions would convert more gas to stars and lead to a higher specific frequency of globular clusters. In both cases, variations in the distribution of angular momentum content could explain the differences in the relative frequency of blue to red clusters. We leave these interesting questions to future work.

4. CONCLUSIONS

We have given a quantitative model for the formation of globular clusters based on the early work of Gunn and McCrea. Clusters are assumed to form in merger-induced collisions. We make use of recent H i data for dwarf irregular galaxies and earlier observational work to derive the key parameters of the model. We then combined this model with a simple chemical evolutionary model to predict the metallicity distributions of stars formed before and during these mergers. These predictions were compared with relatively recent survey data and shown to be consistent with both models. As additional data become available, it will be possible to refine these ideas into a more sophisticated picture for galaxy evolution.

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