BULGE GLOBULAR CLUSTERS IN SPIRAL GALAXIES

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ABSTRACT

There is now strong evidence that the metal-rich globular clusters (GCs) near the center of our Galaxy are associated with the Galactic bulge rather than the disk as previously thought. Here we extend the concept of bulge GCs to the GC systems of nearby spiral galaxies. In particular, the kinematic and metallicity properties of the GC systems favor a bulge rather than a disk origin. The number of metal-rich GCs normalized by the bulge luminosity is roughly constant (i.e., bulge S_b ∼ 1) in nearby spiral galaxies, and this value is similar to that for field elliptical galaxies when only the red (metal-rich) GCs are considered. We argue that the metallicity distributions of GCs in spiral and elliptical galaxies are remarkably similar and that they obey the same correlation of mean GC metallicity with host galaxy mass. We further suggest that the metal-rich GCs in spiral galaxies are the direct analogs of the red GCs seen in elliptical galaxies. The formation of a bulge/spheroidal stellar system is accompanied by the formation of metal-rich GCs. The similarities between GC systems in spiral and elliptical galaxies appear to be greater than the differences.

Subject headings: galaxies: formation — galaxies: individual (M31, M81, M104) — galaxies: star clusters

1. INTRODUCTION

Globular clusters (GCs) in our Galaxy can be broadly divided into two classes on the basis of their metallicity and/or kinematics (e.g., Zinn 1985). The metal-poor, nonrotating subpopulation has long been associated with the Galaxy halo. The metal-rich GC system is spherically distributed about the Galaxy center from Keck spectra. They derive a velocity dispersion of 150 ± 20 km s⁻¹ for over 200 GCs in the M31 system. They find a velocity dispersion of 146 ± 12 km s⁻¹. This is consistent with the central stellar velocity dispersion of 150 km s⁻¹ (van den Bergh 1999). Furthermore, the metal-rich GCs reveal solid-body–like rotation within 5 kpc with an amplitude similar to that of the stellar rotation curve, which is dominated by the bulge at these small radii (e.g., Rubin & Ford 1970). They also find that the metal-rich GC system is spherically distributed about the galaxy center. Thus, the inner metal-rich GCs in M31 reveal the same features that have led previous workers to associate equivalent GCs in our Galaxy with the bulge.

2.2. M81

The GC system of M81 (Sa/Sb) is less well studied than M31, but both photometric (Perlmutter & Racine 1995) and kinematic (Perlmutter, Brodie, & Huchra 1995; Schroder et al. 2001) studies have noted similarities to the Milky Way’s GC system. Schroder et al. (2001) give the kinematics for the metal-rich GCs within 2 kpc of the galaxy center from Keck spectra. They derive a velocity dispersion of 152 ± 36 km s⁻¹ and rotation velocity of 96 ± 56 km s⁻¹. Measurements of the stellar central velocity dispersion vary from 150 to 180 km s⁻¹, with a median value of 167 km s⁻¹. The stellar rotation curve for M81 peaks at around 0.5 kpc radius with a value of ~110 km s⁻¹ (Heraudeau & Simien 1998). The stellar values are slightly higher than those inferred for the GC system but are well within the errors. Although the evidence is less strong, the inner metal-rich GCs of M81 have kinematic properties that are consistent with the bulge.

3. GLOBULAR CLUSTER METALLICITIES

Individual metallicities are now available for over 250 GCs in M31 (Barmby et al. 2000). For M81, the photometry of Per-
The situation is even more pronounced. Restricted to the GCs to within 5 kpc of the galaxy center, then than the disk component (see also § 4). If the samples are re-
is tempting to associate the metal-rich GCs with the bulge rather galaxies. Since M104 has a tiny disk and a dominant bulge, it poor GCs is significantly higher in M104 than the other spiral galaxies. Since M104 has a tiny disk and a dominant bulge, it is tempting to associate the metal-rich GCs with the bulge rather than the disk component (see also § 4). If the samples are re-
stricted to the GCs to within 5 kpc of the galaxy center, then the situation is even more pronounced.

M33 (Sc) at the opposite extreme has very few GCs with [Fe/H] > −1. Its “bulge” has a luminosity of $M_V \sim −15$ (Bo-thun 1992). Local Group dwarf galaxies of this luminosity typically have less than half a dozen GCs. Thus, if the M33 bulge is analogous to a small galaxy, few associated GCs are expected. We note that the LMC (another bulgeless galaxy) also lacks metal-rich GCs. For M31 (Sb) and the Milky Way (Sbc), the number of metal-rich GCs (relative to metal-poor ones) is intermediate between M104 (Sa) and M33 (Sc). We note that Kissler-Patig et al. (1997) associate the red GCs in the S0 galaxy NGC 1380 with that galaxy’s bulge. It seems likely that the relative number of metal-rich GCs is related to the host galaxy Hubble type and hence the relative importance of a galaxy’s bulge.

How are the metal-rich and metal-poor subpopulations in spiral galaxies related to those seen in early-type galaxies? Historically, one difference between the GC metallicity distributions in spiral and elliptical galaxies was thought to be the mean metallicity of the two peaks. M104, M31, and the Milky Way all have GC subpopulations with mean metallicities of [Fe/H] ~ −1.5 and −0.5 (see Fig. 1), while elliptical galaxies were thought to have GC mean values of [Fe/H] ~ −1.0 and 0.0 (Harris 1991). Recently, two developments have caused us to reassess the mean GC metallicity in elliptical galaxies toward lower metallicities. The first effect is the use of more accurate transformations from optical colors to [Fe/H]. For example, the new transformation of Kissler-Patig et al. (1998) converts a typical $V-I = 1.05$ to [Fe/H] = −1.07, where the old Galactic-based transformation would give [Fe/H] ~ −0.5 (Couture, Harris, & Allwright 1990). The second effect is that the more accurate Galactic extinction values of Schlegel, Finkbeiner, & Davis (1998) tend to be larger on average by up to $A_V \sim 0.1$ than the traditionally used Burstein & Heiles (1984) values. Thus, extinction-corrected GC colors are now bluer than before and more metal-poor when transformed. If these two effects are taken into account, the two GC subpopulations in elliptical galaxies have mean metallicities of [Fe/H] ~ −1.5 and −0.5, which is similar to those in spiral galaxies. To first order, there appears to be very little difference between the mean metallicity of the two subpopulations in late- and early-type galaxies.

When GC metallicities are examined in still more detail, it is found that the mean GC color (metallicity) correlates with galaxy velocity dispersion for early-type galaxies (Forbes & Forte 2001; Larsen et al. 2001a). Do the bulge GCs of spiral galaxies follow the same relation as early-type galaxies?

We have collected a sample of 37 early-type galaxies from the literature with bimodal GC color distributions. The mean color of the metal-rich subpopulation has been corrected to a common $V-I$ color (Forbes & Forte 2001) and corrected for extinction using Schlegel et al. (1998). To this sample we add M104, M31, and the Milky Way GC systems. The $V-I$ color of the M31 and Milky Way metal-rich GCs have been calculated using the transformations of Barmby et al. (2000). Central velocity dispersions come from Gebhardt et al. (2000) and Kent (1992). The uncertainty in the mean color is rarely quoted in the original works. We have decided to adopt relatively conservative error estimates (i.e., $\pm 0.03$ for $HST$ data with definite bimodality, $\pm 0.05$ for probable bimodality, and $\pm 0.08$ for ground-based data to reflect the higher photometric errors and contamination rates). They may be smaller than we assume since the scatter in the data points is generally less than the errors. This means that we will tend to underestimate the significance of any slope compared to the error on the slope from a least-squares fit.

The data are shown in Figure 2. For the early-type galaxies, the Spearman rank correlation indicates that the red GCs are correlated with galaxy velocity dispersion with a probability of 99.9%. A least-squares fit gives a positive slope (similar to that found by Forbes & Forte 2001 and Larsen et al. 2001a for smaller samples) at the 4 $\sigma$ level. The mean colors of the

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1 The combined sample data are available at http://astronomy.swin.edu.au/staff/dforbes/glob.html.
metal-rich GC subpopulations in the three spiral galaxies are also plotted in Figure 2. The red GCs in spiral galaxies are consistent with the metallicity–velocity dispersion relation for early-type galaxies.

If we use only the high-quality sample (i.e., HST data with definite bimodality), then the Spearman test gives 99.5% and a slope of 4σ. An unweighted fit to the high-quality sample gives a similar slope, with slightly increased significance of 5σ.

4. BULGE SPECIFIC FREQUENCY

Traditionally, GC specific frequency $S_{\nu}$ refers to the total number of GCs per galaxy luminosity, normalized to $M_V = -15$. Harris (1981) was the first to compare total GC numbers in spiral galaxies with the luminosity of the bulge component. Recently, Cote et al. (2000) pointed out that $S_{\nu}$ defined in this manner was indistinguishable for spiral and elliptical galaxies in similar environments. Here we focus on the metal-rich/red GCs in spiral/elliptical galaxies compared to the bulge luminosity (we assume that elliptical galaxies are bulge-dominated systems). We refer to this as the bulge $S_{\nu}$.

The total number of GCs and the number of metal-rich GCs are given by Larsen et al. (2001b) for M104 and in the compilation of Forbes et al. (2000) for M31 and the Milky Way. These numbers and the host galaxy magnitudes discussed below are summarized in Table 1. From the galaxy total magnitudes, we calculate the bulge and disk magnitudes using the following method. The bulge-to-total (B/T) luminosity for M104 has been given by Kent (1988) as 0.85 and by Baggett, Baggett, & Anderson (1998) as 0.73. Here we use 0.8. For M31 (Sb) and the Milky Way (Sbc), we use the B/T variations with Hubble type of Simien & de Vaucouleurs (1986), i.e., B/T = 0.25 and B/T = 0.19, respectively, with a dispersion of about ±0.05 within a given Hubble type. For the disk contribution, we assume that the halo light is negligible and hence all of the remaining light comes from the disk.

In §2, we argued, mostly from the kinematic data, that the bulk of metal-rich GCs in spiral galaxies are not associated with the disk but rather the bulge component. Further support for this idea comes from examining the number of metal-rich GCs per unit starlight. The GC system of M104 provides a key data point. For M104, the total number of red GCs and the disk magnitude combine to give a disk $S_{\nu}$ of 4.4 ± 5.2. Assuming that the disks in M31 and the Milky Way have similar stellar populations (i.e., MIL), the disk $S_{\nu}$ of M104 is about 20 times that of these other spiral galaxies. This large variation in disk $S_{\nu}$ suggests that the bulk of metal-rich GCs in spiral galaxies are not, in fact, disk objects.

From the bulge magnitudes and number of metal-rich GCs given above, we derive bulge $S_{\nu}$-values of 1.1 ± 0.8 (M104), 0.6 ± 0.3 (M31), and 0.8 ± 0.9 (Milky Way). Unlike the disk $S_{\nu}$-values, bulge $S_{\nu}$-values are fairly consistent between the three spiral galaxies.

In the case of the Milky Way, only GCs within ~5 kpc show bulge characteristics, while those further out have been associated with the thick disk (Minniti 1995; Cote 1999). In terms of the bulge effective radius, 5 kpc is $2R_{eff}$ (van den Bergh 1999). The bulge effective radii for M104 and M31 are 8 kpc (Bender, Burstein, & Faber 1992) and 2.5 kpc (van den Bergh 1999), respectively. If the metal-rich GC samples in M104 and M31 are 8 kpc (Bender, Burstein, & Faber 1992) and 2.5 kpc (van den Bergh 1999), respectively. If the metal-rich GC samples in M104 and M31 are 8 kpc (Bender, Burstein, & Faber 1992) and 2.5 kpc (van den Bergh 1999), respectively. If the metal-rich GC samples in M104 and M31 are restricted to within $2R_{eff}$, then we estimate about 375 metal-rich GCs in M104 (from Larsen et al. 2001b) and 61 in M31 (from Barnby et al. 2000). The Milky Way has about 35

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**TABLE 1**

| Parameter                  | M104          | M31           | Milky Way  |
|---------------------------|---------------|---------------|------------|
| Globular cluster total    | 1150 ± 575    | 400 ± 55      | 160 ± 20   |
| Metal-rich clusters (all radii) | 667 ± 333     | 100 ± 14      | 53 ± 7     |
| Metal-rich clusters (<2R_{eff}) | 378 ± 189    | 61 ± 8        | 35 ± 4     |
| Galaxy total $M_V$        | -22.2 ± 0.1   | -22.0 ± 0.2   | -21.3 ± 0.3|
| Bulge-to-total ratio      | 0.80 ± 0.05   | 0.25 ± 0.05   | 0.19 ± 0.05|
| Disk $S_{\nu}$ (all radii) | 4.4 ± 5.2     | 0.2 ± 0.1     | 0.2 ± 0.1  |
| Bulge $S_{\nu}$ (<2R_{eff}) | 1.1 ± 0.8     | 0.6 ± 0.3     | 0.8 ± 0.9  |
| Bulge $S_{\nu}$ (<2R_{eff}) | 0.6 ± 0.5     | 0.4 ± 0.2     | 0.6 ± 0.6  |

**Note:** Total number of globular clusters, the metal-rich subpopulation, and those within twice the bulge $R_{eff}$. The bulge and disk specific frequencies, $S_{\nu}$, use bulge and disk luminosities, respectively.

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**FIG. 2**—Mean color of the red (metal-rich) GC subpopulations vs. log galaxy velocity dispersion. Early-type galaxies are shown by filled circles and spiral galaxies by triangles. A typical velocity dispersion error is shown in the lower left. The solid line shows the best fit to the early-type galaxies (slope = 0.26 ± 0.06, intercept = 0.56 ± 0.14). The correlation is significant at the 4σ level. The three spiral galaxies (MW, M31, M104) are consistent with the overall early-type galaxy relation.
known metal-rich GCs within $2R_{\text{eff}}$. Thus, the bulge $S_N$-values within $2R_{\text{eff}}$ are $0.6 \pm 0.5$, $0.4 \pm 0.2$, and $0.6 \pm 0.6$ for M104, M31, and the Milky Way, respectively. Within the errors, the bulge $S_N$-values for M104, M31, and the Milky Way are consistent. So although the three spiral galaxies span a range of Hubble types from Sa to Sbc, the bulge $S_N$ appears to be nearly constant for spiral galaxies.

In each case, there is a tendency to miss some metal-rich GCs, as they are harder to detect near galaxy centers. For example, about a dozen GCs are thought to be hidden from our view in the Milky Way (van den Bergh 1999). Recently, the Two Micron All Sky Survey has detected two more metal-rich bulge GCs (Hurt et al. 2000). Barmby et al. (2000) give photometry for about two-thirds of the total GC population in M31, which has an estimated total population of 400 ± 55. Again, many of the missing GCs will be associated with the bulge. The derived bulge $S_N$-values may be underestimated by up to 30%.

How do the bulge $S_N$-values for spiral galaxies compare to elliptical galaxies? Field elliptical galaxies have total $S_N$-values of 1–3 (Harris 1991). The fraction of red GCs in elliptical galaxies is typically about half (e.g., Forbes, Brodie, & Grillmair 1997). For example, wide-area studies of the field/group elliptical galaxies NGC 1052 and NGC 1700 found red fractions and total $S_N$-values of 0.50, 1.7 and 0.56, 1.3, respectively (Forbes, Georgakakis, & Brodie 2001; Brown et al. 2000). This implies that field elliptical galaxies typically have bulge $S_N$-values of 0.5–1.5. Thus, field elliptical galaxies have similar bulge $S_N$-values to field spiral galaxies. This provides further support for our claim that the metal-rich GCs in spiral galaxies and those in elliptical galaxies have the same origin; i.e., they formed along with the bulge stars. We note that cluster elliptical galaxies may have similar $S_N$-values when the mass of hot gas is taken into account (McLaughlin 1999). Little is known about the GC systems of cluster spiral galaxies.

5. CONCLUDING REMARKS

From globular cluster (GC) kinematic information, we have argued that the inner, metal-rich GCs in the nearby spiral galaxies M31 and M81 have a bulge origin. On the basis of GC numbers and specific frequency, we showed that the metal-rich GCs in the Sa spiral galaxy M104 are most likely associated with the dominant bulge rather than the small disk component. The derived bulge specific frequency for the GCs in M104, M31, and the Milky Way are consistent with a constant value of ~1. This is similar to the value for field elliptical galaxies (when only the metal-rich GCs are considered) but is less than that for cluster elliptical galaxies. The metallicity distributions of GCs in late- and early-type galaxies are similar to first order and obey the same correlation of mean GC metallicity with host galaxy velocity dispersion. This relation indicates a common chemical enrichment history for the metal-rich GCs and the host galaxy (Forbes & Forte 2001).

We conclude that the majority of the metal-rich GCs in spiral galaxies are associated with the galaxy bulge and that these GCs are the analogs of the red (metal-rich) GCs in giant elliptical galaxies. Thus, GC systems provide another example of the similarity between elliptical galaxies and spiral bulges (e.g., Wyse, Gilmore, & Franx 1997). By extension, this would suggest that bulges and elliptical galaxies formed by a similar mechanism. In the case of the Milky Way bulge, van den Bergh (1999) concluded that it was formed by a rapid but clumpy collapse.

In the multiphase collapse model for GC formation proposed by Forbes et al. (1997), the “bulge” of a giant elliptical galaxy occurred in the second or galactic phase. The red GCs formed during this phase. In that paper, we associated the metal-rich GCs of spiral galaxies with disks and speculated that they were a third phase of GC formation. It now seems likely that the bulk of metal-rich GCs in spiral galaxies were formed along with the bulge stars, and it is these that are directly analogous to red GCs in giant elliptical galaxies.

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