Globular Clusters in the Sombrero Galaxy (NGC 4594) \(^1,2\)

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ABSTRACT
The Sombrero galaxy, NGC 4594, contains the most numerous globular cluster system of any nearby spiral. It is an ideal candidate in which to study the globular clusters and contrast them with those in Local Group spirals. Here we present B and I imaging from the CTIO Schmidt telescope which gives a field-of-view of \(31' \times 31'\). Using DAOPHOT we have detected over 400 globular clusters and derived their magnitudes, B–I colors and photometric metallicities. We have attempted to separate our sample into disk and bulge/halo globular cluster populations, based on location in the galaxy. There is some evidence that the disk population is more metal–rich than the bulge/halo globular clusters, however contamination, dust reddening and small number statistics makes this result very tentative. We find that the median metallicity of the bulge/halo globular clusters is \([\text{Fe/H}] = -0.8\). This metallicity is consistent with previous estimates based on smaller samples. It is also similar to the metallicity predicted by the globular cluster metallicity – galaxy luminosity relation. As with our Galaxy, there is no radial metallicity gradient in the halo globular clusters. This suggests that the spheroidal component of NGC 4594 did not form by a dissipational process.

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1. Introduction

Measurement of the abundances of Milky Way globular clusters (GCs) have provided important clues on the formation and chemical enrichment history of the Galaxy. Combined with kinematics, a clear dichotomy of metal–rich disk GCs and metal–poor halo GCs have been identified (e.g. Zinn 1985). The disk and halo GCs have a mean metallicity of $[\text{Fe}/\text{H}] = -0.6$ and $-1.6$ respectively (e.g. Ashman & Bird 1993). Globular clusters in our sister galaxy, M31, have been relatively well–studied so that spectroscopic metallicity measurements are available for about half of them (Huchra, Brodie & Kent 1991). A bimodal metallicity distribution is not as obvious for M31 but the analysis of Ashman & Bird (1993) indicates peaks at $[\text{Fe}/\text{H}] = -0.6$ and $-1.5$, i.e. similar to the Milky Way. The other Local Group spiral, M33, has about 30 known GCs, of which spectroscopic metallicities have been obtained for 22 (Brodie & Huchra 1991). The mean metallicity of $[\text{Fe}/\text{H}] = -1.55 \pm 0.37$ is similar to that of Milky Way and M31 halo GCs. The small number of GCs makes it difficult to convincingly identify a population of disk GCs.

Beyond the Local Group the nearest spirals are M81 (m–M = 27.8) and NGC 4594 (m–M = 29.73). Perelmuter & Racine (1995) estimated from imaging of M81 that it contains $\sim 200$ GCs. Spectra for 30 GCs have been obtained (Brodie & Huchra 1991; Perelmuter, Brodie & Huchra 1995) which give a mean $[\text{Fe}/\text{H}] = -1.48 \pm 0.19$. The Sombrero galaxy, NGC 4594, is a giant Sa galaxy ($M_V = -22.0$) with almost 2,000 GCs (Bridges & Hanes 1992). This is significantly more than either the Milky Way with $N_{GC} = 160 \pm 20$ or M31 with $N_{GC} = 350 \pm 100$ (Harris 1996). It is also nearly edge–on ($i = 38^\circ$) so that GCs projected close to the galaxy major axis can be used to define a plausible sample of disk GCs. Separating disk and halo GCs in M31 ($i = 38^\circ$) has been a major source of uncertainty. Thus NGC 4594 is an ideal candidate in which to study the GC system of another spiral galaxy.

The distance to NGC 4594, from the average of the surface brightness fluctuation and planetary nebulae luminosity function methods, is $8.8 \pm 0.4$ Mpc (Ciardullo, Jacoby & Tonry 1993). At this distance GCs range in magnitude from $B \sim 18–27$, so that only the brightest few GCs are accessible spectroscopically by today’s large telescopes. A valiant effort was made recently by Bridges et al. (1996). After 7 hours of integration time over 4 nights of observing with the 4.2m William Herschel Telescope, they obtained spectra of 34 confirmed GCs. Unfortunately their spectra were not of sufficient quality to determine a metallicity for individual GCs. Summed together they derived a mean of $[\text{Fe}/\text{H}] = -0.7 \pm 0.3$. An alternative approach, is to obtain GC colors from imaging studies. Imaging has the advantage of being very efficient and photometric metallicities can be derived from the Galactic GC color–metallicity relation (Couture et al.

The GC system of NGC 4594 has been studied photometrically by Harris et al. (1984) and Bridges & Hanes (1992). The first of these was a wide field–of–view photographic study in U and V bands. They examined the spatial distribution and estimated the GC specific frequency. The second study targeted three areas of the galaxy and imaged these in B and V bands with a $2.2 \times 3.6$ CCD. From the B–V colors of 131 GCs they derived a mean $[\text{Fe}/\text{H}] = -0.81 \pm 0.25$ for the GC system. Here we present 31’ × 31’ field–of–view CCD imaging of NGC 4594 in B and I bands. We measure B–I colors which are about twice as sensitive to metallicity as B–V colors (e.g. Geisler, Lee & Kim 1996). Our wide field–of–view imaging allows us to define spatially samples of ‘disk’ and ‘bulge/halo’ GCs, and examine their metallicity distributions.

2. The Data and Globular Cluster Selection

Broad–band B and I images of NGC 4594 were taken with the Cerro Tololo Interamerican Observatory (CTIO) Schmidt telescope. We used a Thomson 1024 × 1024 array with a pixel scale of 1.84“/pixel. The images were obtained in 1994 February 12 and 13. Reduction was carried out in the standard way (i.e. bias and dark subtraction, flat–fielding and sky subtraction). The total exposure times were 7200 and 2400 secs for the B and I images respectively. After combining, the B image was calibrated using aperture photometry from the UBV catalog of of Longo & de Vaucouleurs (1983) which gave an rms accuracy of $\pm 0.06$ mag. Burkhard (1986) found that the bulge had a near constant color of $B–I = 2.7 \pm 0.1$ and this was used to calibrate the I image. Finally, the magnitudes are corrected for Galactic extinction of $A_B = 0.12$ and $A_I = 0.05$ (Bender et al. 1992). Typical photometric errors are 0.08 at $B = 20.5$ and 0.18 at $B = 21.5$. Our B–I colors are transformed into $[\text{Fe}/\text{H}]$ values using the color–metallicity relation of Couture et al. (1990)
which is based on Milky Way GCs. This relation is calibrated from about 1/100 solar metallicity up to solar. The typical random error in this transformation is $\pm 0.15$ dex in [Fe/H]. From the final images, we subtracted a smooth elliptical model for the bulge using IRAF software.

Contamination from foreground stars and background galaxies is a concern for most GC imaging studies. Although not ideal, one method is to obtain similar exposure time images in some nearby ‘blank’ field and process these images in the same way as the actual data. This provides a statistical contamination correction. We do not have such a ‘blank’ field, so we attempt to estimate the contamination using star and galaxy surface densities from the literature. Before applying this method we will restrict candidate GCs to magnitudes of 17.5 $< B < 22$. The faint limit is a little brighter than the expected turnover of the GC luminosity function (i.e. $B \sim 22.5$) and was chosen to ensure that a color bias was not introduced. The bright limit is at least $3\sigma$ from the turnover magnitude assuming a dispersion characteristic of the Milky Way and M31 (Secker & Harris 1993), while excluding the most obvious foreground stars.

The number of foreground stars can be estimated from the Bahcall & Soneria (1981) model of the Milky Way. For our $31' \times 31'$ image in the direction of NGC 4594, their model predicts about 750 stars with $17.5 < B < 22$. Using figure 1 of Koo & Kron (1992), we estimate our image contains about 220 background galaxies down to $B = 22$. Thus the total contamination in our image from stars and galaxies, before any color selection, is about 970 for magnitudes $17.5 < B < 22$. To compare this number with the number of objects in the B image, we have used DAOPHOT with a fairly conservative detection threshold of $5\sigma$ per pixel. This gives $\sim 1400$ objects with $17.5 < B < 22$. Thus we estimate our image contains $\sim 430$ bona fide GCs. Based on our detection limit and an expected turnover magnitude of $B \sim 22.5$, our sample represents about 1/3 of the total GC population. So the total number of GCs is $\sim 1300$, which is at the lower limit of the range estimated by Bridges & Hanes (1992) i.e. $1900 \pm 600$. We note that although we have only detected a fraction of the total GC population, there is no known correlation of GC metallicity with luminosity or mass (Huchra, Brodie & Kent 1991) which might otherwise have bias our results.

Although stars and galaxies cover a similar range of B–I colors as GCs, we know from other studies that the vast majority of GCs have metallicities $-2 < [\text{Fe/H}] < +0.5$ (i.e. $0.15 < B-I < 2.33$). So excluding objects beyond these values will preferentially remove stars and galaxies from the object lists. After applying this metallicity (color) selection and making restrictions in the DAOPHOT sharpness and roundness parameters, our sample consists of 457 candidate GCs. This is similar to the $\sim 430$ objects left after a statistical correction for stars and galaxies has been applied. From these arguments we expect that the majority of objects in our final list are indeed GCs.

Next we attempt to divide the sample into ‘disk’ and non–disk (which we will call ‘bulge/halo’) GCs. In our Galaxy (Gilmore & Reid 1983) and NGC 4594 (Burkehead 1986) the scale height of disk stars is $Z \sim 1$ kpc. Disk GCs in our Galaxy can reach distances above the plane of $Z \leq 4$ kpc. We have chosen to define disk GCs in NGC 4594 as those with scale heights $|Z| \leq 4$ kpc. The colors of the disk objects may be reddened by the galaxy’s dust lane. To minimize this effect we have excluded objects that are close to the central dust i.e., objects with major axis distances of less than 5 kpc of the galaxy center. Conversely bulge/halo GCs are simply defined as those with $|Z| > 4$ kpc; it is not clear whether such GCs are associated with the dominant bulge or the halo. Dividing the sample in this way we have 79 disk objects and 378 halo objects. Due to projection effects some bulge/halo GCs will be present in the disk sample. From the surface density of halo GCs we estimate that between 1/3 and 1/2 of the disk GCs are not associated with the disk.

3. Results and Discussion

In this section, we first discuss the GC sample of Bridges et al. (1996). Second, we examine the GC metallicity distribution in NGC 4594 and finally we search for spatial abundance gradients in this distribution.

After superposing the position of the Bridges et al. 34 spectroscopically–confirmed GCs on our CCD images we managed to measure B and I magnitudes for 24 (the others are presumably fainter than our limiting magnitude). The mean color is $B-I = 1.9 \pm 0.2$ (error on the mean), which corresponds to $[\text{Fe/H}] = -0.7 \pm 0.5$. This is reassuringly consistent with the spectroscopic mean metallicity, for all 34 GCs, of $[\text{Fe/H}] = -0.7 \pm 0.3$. This suggests that the transformation from color to metallicity is reasonable.
In Fig. 1 we show the metallicity distribution for disk (|Z| ≤ 4 kpc) and bulge/halo (|Z| > 4 kpc) objects. The median metallicity of the bulge sample is [Fe/H] = –0.8. This is similar to that obtained by Bridges et al. (1996) and suggests that our sample is dominated by bona fide GCs. As pointed out by Bridges et al. the GC metallicity is more comparable to that found in giant ellipticals than other spirals. However this might be expected given the claimed correlation of GC metallicity with parent galaxy luminosity (e.g. Brodie & Huchra 1991). Using the recent best–fit of Forbes et al. (1996) and the bulge luminosity of NGC 4594, the relation predicts a GC system mean metallicity of [Fe/H] = –0.6 ± 0.3 (rms error). The disk sample has a median metallicity of [Fe/H] = –0.5. As the disk sample will include a significant fraction of bulge GCs, the average metallicity of the disk sample is likely to be somewhat higher than – 0.5. If we separate the 24 Bridges et al. (1996) GCs, with available B–I colors, into bulge and disk systems, then their metallicities are [Fe/H] = –1.2 and –0.1 respectively. Thus there is some tentative evidence, from both our sample and that of Bridges et al. that NGC 4594 contains a population of disk GCs that are slightly more metal–rich than non–disk GCs. Although it is difficult to rule out preferential reddening of the GCs by dust, we do not think this has had a strong effect on the disk GC colors. First, we have excluded the inner galaxy regions with the obvious dust lane. Second, we do not find a strong radial GC color gradient in either scale height (see Fig. 2) or along the major axis as might be expected from centrally concentrated dust. The possibility that inner GCs are intrinsically blue (and so removing a reddening trend due to dust) is very unlikely given studies of other galaxies (e.g. Harris 1991; Geisler et al. 1996).

Abundance gradients, or lack of, provide useful constraints to galaxy formation models. For example, the absence of an abundance gradient in Milky Way halo GCs supports the view of Searle & Zinn (1978) in which the halo is made up of small protogalactic fragments, rather than arising from a pure dissipational collapse. In the M31 GCs the situation is more uncertain. Huchra, Brodie & Kent (1991) found that there exists a upper envelope in GC metallicity with galactocentric radius but also pointed out that selection effects and contamination by disk GCs made evidence for an abundance gradient inconclusive. In Fig. 2 we show the spatial variation of GC metallicity for the disk and bulge/halo samples. In the lower panel of Fig. 2 we show GC metallicity versus projected galactocentric radius for the bulge/halo objects. As with the Milky Way GC system, there is no statistically significant metallicity gradient. This constrains the role of dissipation in forming the spheroidal component of NGC 4594. In a dissipational collapse one expects a metallicity gradient in the direction of the collapse e.g., perpendicular to a disk. Accretion of material may reduce the strength of such gradients. Our Galaxy shows a weak trend of GC metallicity with scale height, where the slope is –0.084 ± 0.031 dex kpc$^{-1}$ (Armandroff 1993). In the upper panel of Fig. 2 we show the metallicity of disk GCs versus scale height from the major axis. The data show a hint of a weak trend with scale height, but it is not formally significant.

4. Conclusions

After separating a sample of ~ 450 globular clusters in NGC 4594 with photometric metallicities into spatially–defined ‘disk’ and ‘bulge/halo’ subsystems, we find tentative evidence for a difference in the metallicity of the two populations. The bulge/halo globular clusters have a median metallicity of [Fe/H] = –0.8 whereas the disk globulars have [Fe/H] ≥ –0.5. Contamination, dust reddening and a small number of disk globular clusters make it difficult to confidently ascribe a higher average metallicity to the disk population. The metallicity of the bulge/halo system is greater than that of the Milky Way ([Fe/H] = –1.6) or M31 ([Fe/H] = –1.5) halo globulars, however it is consistent with that expected from the correlation of globular cluster metallicity with galaxy luminosity. Like the Milky Way, we find no evidence for a metallicity gradient in the bulge/halo globular cluster population. This argues against formation of the spheroidal component by dissipational collapse.

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Fig. 1.— Metallicity distribution of globular cluster candidates in NGC 4594. The upper panel (the ‘disk’ sample) shows objects with scale height $|Z| \leq 4$ kpc (excluding the inner galaxy regions). The median metallicity is $[\text{Fe/H}] = -0.5$ although there is clearly a large range in metallicities. The lower panel (the ‘bulge/halo’ sample) shows objects beyond 4 kpc from the galaxy disk. The median metallicity is $[\text{Fe/H}] = -0.8$. There is tentative evidence that the disk globular clusters are more metal–rich than the bulge/halo globular clusters.
Fig. 2.— Spatial variation of globular cluster metallicity in NGC 4594. The upper panel shows the variation of metallicity with scale height for the disk sample (i.e. $|Z| \leq 4$ kpc). There is no statistically significant gradient. The lower panel shows the radial variation of metallicity for the bulge/halo sample (i.e. $|Z| > 4$ kpc). As with the Milky Way, there is no statistically significant radial metallicity gradient.