NEAR-INFRARED PHOTOMETRY OF THE CORE-COLLAPSED METAL-POOR GLOBULAR CLUSTERS
NGC5946 AND NGC7099

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ABSTRACT

Moderately deep near-infrared images are used to investigate the photometric properties and spatial distribution of bright giants near the centers of the core-collapsed globular clusters NGC5946 and NGC7099. The former cluster is located at a low Galactic latitude and is heavily reddened; nevertheless, the $K, J-K$ color-magnitude diagram (CMD) shows a well-defined giant branch, with a width $\pm 0.05$ magnitudes in $J-K$. Most of the observed width is due to differential reddening. The upper giant branch is relatively steep, and comparisons with less reddened clusters indicate that (1) NGC5946 must be very metal-poor, with $[\text{Fe/H}] \sim -2$, and (2) $E(B-V) \sim 0.6$. The distance to NGC5946 derived using the near-infrared brightness of the giant branch tip is in excellent agreement with that computed from the $V$ brightness of the HB if $E(B-V) = 0.6$.

The NGC7099 giant branch terminates $\sim 1$ mag fainter in $K$ than the expected tip brightness. The integrated $J-K$ color of NGC7099 changes with radius, such that $\Delta(J-K)/\Delta log(r) = 0.05 - 0.09$, depending on the technique used to measure colors. Similar radial variations in stellar content might be expected in NGC5946; however, the integrated $J-K$ color of this cluster remains constant with radius and, after removing the brightest resolved stars, a color gradient is seen that is in the opposite sense to that in NGC7099. The relative density of bright giant branch stars also remains constant within 30 arcsec of the center of NGC5946. Therefore, it is concluded that NGC5946 does not contain stellar content gradients similar to
those seen in NGC7099 and other post core-collapsed clusters.
I. INTRODUCTION

A large number of globular clusters are located at low Galactic latitudes, with lines of sight that pass through the disk and bulge of the Galaxy. Differential reddening and field star contamination complicate efforts to measure fundamental parameters such as metallicity, reddening, and distance for many of these objects. Despite these inherent difficulties, studies of low Galactic latitude globular clusters are potentially of great importance. For example, if the earliest episodes of star formation occurred near the center of the Galaxy, where the density of primordial star-forming material may have been highest, then the oldest, most metal-deficient clusters should be found in the general vicinity of the Galactic Center. Moreover, it has long been realised that the spatial distribution of clusters at low Galactic latitudes can be used to estimate the distance to the Galactic Center (e.g. Shapley 1918; Racine & Harris 1989). Finally, it appears that the structural properties of clusters are related to distance from the Galactic Center and height above the disk (Chernoff & Djorgovski 1989), so studies of low latitude clusters may provide a means of probing the external forces that act on clusters.

The effects of differential reddening and foreground contamination can be reduced by observing at wavelengths longward of 1\(\mu\)m. Indeed, the selective extinction in \(K\) is roughly a tenth that in \(V\) (e.g. Rieke & Lebofsky 1985), while the contrast between the brightest stars and the main body of the cluster is greatly enhanced in the infrared. The latter point is important for efforts to study stars in the dense central regions of clusters, where the
relative field star contamination is smallest. In the present paper, we use near-infrared photometric observations to investigate the fundamental properties of NGC5946, a low-latitude globular cluster. NGC5946 is located in a very crowded field, and is heavily reddened, with $E(B-V)$ in the range $0.5 - 0.6$ (Alcaino et al. 1991, and references therein). The cluster is very compact, with a light profile indicative of core collapse (e.g. Trager, King, & Djorgovski 1995). The only published color-magnitude diagram (CMD) is that presented by Alcaino et al. (1991), which is based on moderately deep $B$ and $V$ CCD images. The effects of differential reddening are readily evident in the width of the red giant branch (RGB), which is roughly 0.3 mag in $B-V$, and the scatter in the horizontal branch (HB), which amounts to almost 1 mag in $V$.

The metallicity of NGC5946 is uncertain. The integrated spectroscopic properties of NGC5946 are suggestive of $[\text{Fe/H}] \sim -1.4$ (Hesser & Shawl 1986; Armandroff & Zinn 1988; Brodie & Hanes 1986), while Zinn & West (1984) conclude that $[\text{Fe/H}] \sim -1.37 \pm 0.15$ based on the $Q_{39}$ index. However, Bica & Pastoriza (1983) derive $[\text{Fe/H}] = -1.56$ from DDO photometry while, based on the location of the giant branch in the CMD and the reddening inferred for the neighboring cluster NGC5927, Alcaino et al. (1991) argue that NGC5946 may be very metal-poor.

Comparisons with clusters at larger projected distances above the Galactic disk can provide valuable insights into the nature of low latitude clusters like NGC5946. One possible comparison cluster is NGC7099. Like NGC5946,
the light profile of NGC7099 contains a central cusp (Trager et al. 1995). The metallicity of NGC7099 is well determined, with [Fe/H] $\sim -2.1$ (Minniti et al. 1993, Geisler, Minniti, & Claria 1992; Zinn & West 1984). NGC7099 has also been the target of numerous photometric studies (e.g. Dickens 1972; Alcaino 1978; Alcaino & Liller 1980; Alcaino & Wamsteker 1982; Bolte 1987; Piotto et al. 1987; Buonanno et al. 1988; Richer, Fahlman, & VandenBerg 1988; Bolte 1989; Piotto et al. 1990; and Cohen & Sleeper 1995), which reveal a rich blue HB population, a conspicuous deficiency of bright giants near the cluster center, and clear evidence for mass segregation.

In the following paper, we discuss near-infrared photometric observations of NGC5946 and NGC7099. The goals of this study are to (1) estimate the metallicity, reddening, and distance of NGC5946; and (2) determine if the radial distribution of stellar content in NGC5946 is like that seen in NGC7099. Details of the observations are discussed in Section 2, while near-infrared CMD’s, two-color diagrams, and aperture color measurements for both clusters are presented in Section 3. In Section 4 the metallicity, distance, and color profile of NGC5946 are examined. A brief summary follows in Section 5.

II. OBSERVATIONS AND REDUCTIONS

The NGC5946 images were recorded on the night of UT January 31, 1994 using the Ohio State Infrared Imager/Spectrograph (OSIRIS – Depoy et al. 1993), which was mounted at the Cassegrain focus of the CTIO 1.5 meter telescope. Each pixel on the 256 x 256 Hg: Cd:Te array subtended 0.47 arc-
sec per side. Two fields, one centered on the cluster core, the other offset 66 arcsec from the cluster center, were observed through standard Caltech-CTIO filters. A number of standard stars from Casali & Hawarden (1992) were observed on this and other nights, and the transformation coefficients derived from these data are in excellent agreement with those measured over the course of many other OSIRIS observing runs (Depoy 1994, private communication).

The data for NGC7099 were recorded on the night of UT May 26 1991 using the University of Hawai‘i Institute for Astronomy infrared camera (Hodapp, Rayner, & Irwin 1992), which was mounted at the Cassegrain focus of the UH 2.2 metre telescope. Like OSIRIS, the detector in the UH camera is a 256 x 256 Hg:Cd:Te array. A single field, centered on the cluster core, was observed through $K'$ (Wainscoat & Cowie 1992) and Caltech-CTIO $J$ filters with an image scale of 0.37 arcsec per pixel. Standard stars from the list published by Elias et al. (1982) were also observed during the course of the observing run, and details of the transformation to the standard system have been discussed by Davidge & Simons (1994).

At least three exposures, each offset slightly from the others on the sky to facilitate the identification and suppression of cosmic rays and bad pixels (ie. ‘dithering’), were recorded of each cluster field. Additional details of the observations, including total integration times and image quality, are listed in Table 1.

The data reduction followed standard lines. Dark frames, recorded im-
mediately following each set of observations, were subtracted from the raw cluster images. The results were divided by sky flats, constructed by median-combining images of various fields recorded on the same night. The flat-fielded images were registered, sky subtracted, and then combined by computing the median intensity at each pixel location, a process that effectively suppresses cosmetic defects and cosmic rays. The final $K$ images of all three fields are shown in Figures 1, 2, and 3.

III. PHOTOMETRIC MEASUREMENTS

The brightnesses of individual stars were measured using the point-spread function fitting routine ALLSTAR (Stetson & Harris 1988), which is part of the DAOPHOT (Stetson 1987) photometry package. The resulting near-infrared measurements were combined, when possible, with $V$ brightnesses from Alcaino et al. (1991 – NGC5946) and Alcaino & Liller (1980 – NGC7099). The brightnesses and colors of those stars with $V, J,$ and $K$ photometry are listed in Tables 2 (NGC5946) and 3 (NGC7099).

The $K, J - K$ diagrams for stars in NGC5946 Fields 1 and 2 with fitting errors, as computed by ALLSTAR, less than 0.07 magnitude in each bandpass are shown in Figure 4. The Field 1 ($K, J - K$) CMD shows a well-defined giant branch sequence, which can be traced from $K \sim 9.4$ to $K \sim 15$. The giant branch is moderately wide, with a dispersion of $\pm 0.044$ mag in $J - K$ when $K \leq 11.75$. The width of the giant branch is determined by a number of factors, including photometric errors, differential reddening, star-to-star abundance differences, and the presence of asymptotic giant branch
(AGB) stars. An upper limit to the smearing introduced by differential reddening can be derived by assuming that the last two factors are negligible. The photometric uncertainties in $J$ and $K$ were estimated from numerical simulations, in which scaled versions of the PSF’s constructed for each field were added to the final frames. The brightnesses of these artificial stars were then measured using DAOPHOT. These simulations indicate that the dispersion in $J - K$ due to photometric errors when $K \leq 11.75$ is $\pm 0.015$ magnitudes. Hence, differential reddening produces no more than $\pm 0.04$ mag widening of the giant branch.

Because it samples a region with lower mean stellar density and was recorded with relatively long exposure times, the Field 2 ($K, J - K$) CMD, shown in the middle panel of Figure 4, extends almost 1 magnitude fainter than that of Field 1. In addition to the cluster sequence, a blue plume of foreground disk stars and blue HB cluster stars is also evident. Contamination from the blue disk component complicates efforts to trace the cluster sequence fainter than $K \sim 16$, which is $\sim 2$ magnitudes brighter than the expected location of the main sequence turn-off.

The ($K, V - K$) diagram for NGC5946 Field 1 is shown in the left hand side of Figure 5. The ($K, V - K$) CMD shows considerable scatter, as $V - K$ is more susceptible to differential reddening than $J - K$, although the upper giant branch and the HB are clearly evident. However, the presence of a blue plume in the Field 2 ($K, J - K$) CMD suggests that some of the blue HB stars may actually be line-of-sight disk stars.
The \((K, J - K)\) and \((K, V - K)\) CMD's for NGC7099 are shown in the right hand panels of Figures 4 and 5, respectively. The giant and HB sequences are clearly evident in both CMD's. The \((K, J - K)\) CMD of NGC7099 is very similar to that published by Cohen & Sleeper (1995), although the current data provides deeper photometric coverage.

The most luminous giants in NGC5946 have intrinsic \(K\) brightnesses over a magnitude brighter than their counterparts in the central regions of NGC7099. The brightest giants in NGC5946 occur at \(K \sim 9.4\), while in NGC7099 the brightest giants have \(K \sim 10.0\). Using the reddenings and HB brightnesses listed in Table IV of Armandroff (1989), and assuming that \(M_{V}^{HB} = 0.6\), then the brightest giants in NGC5946 have \(M_K = -5.5\), while in the central regions of NGC7099 the brightest giants have \(M_K = -4.4\). Hence, there is a deficiency of bright giants in the central parts of NGC7099.

\((K, J - K)\) normal points were derived for NGC5946 and NGC7099 by grouping the observations in \(\pm 0.25\) magnitude bins in \(K\), and then computing the mean \(J - K\) color in each interval. Only the Field 1 observations were used for NGC5946. Outlier points were rejected by applying an iterative \(2 - \sigma\) rejection algorithm, and the results are listed in Table 4.

The \((J - H, H - K)\) diagram for stars in NGC5946 Field 1 brighter than \(K = 13\) is shown in Figure 6. Data for bright giants in the metal-poor clusters M13 and M92 (Cohen, Frogel, & Persson 1978), as well as the sequence defined by solar neighborhood giants (Bessell & Brett 1988), are also shown for comparison. The M13, M92, and solar neighborhood data have
been shifted using the reddening law of Rieke & Lebofsky (1985) to account for the color excess of NGC5946, which is assumed to be $E(B - V) = 0.6$ (Section 4). Although the NGC5946 data show considerable scatter, it is evident that the locus defined by these observations is in rough agreement with the sequence defined by other metal-poor globular clusters.

The $(J - K, V - K)$ diagrams for NGC5946 and NGC7099 are shown in Figure 7, along with the corresponding sequences for giants in M92, M13, and the solar neighborhood. The NGC5946 observations, as well as those for NGC7099, fall to the left of the solar neighborhood sequence, and are in rough agreement with the loci defined by M92 and M13. It is evident that a clear distinction between globular cluster and solar neighborhood giants can be made on the $(J - K, V - K)$ plane, so optical-infrared two-color diagrams should provide a means of identifying non-cluster stars in crowded environments.

There is considerable evidence that dynamical evolution introduces radial variations in stellar content (e.g. Djorgovski & Piotto 1992), and color gradients are one signature of this effect. Using moderately deep images of NGC4147, Davidge (1992) demonstrated that radial color variations in globular clusters can be detected at wavelengths longward of 1µm. Therefore, near-infrared color gradients should be evident in NGC5946 and NGC7099 – is this the case? To answer this question, two different methods were used to measure the near-infrared cluster color profiles. First, direct aperture measurements were made using the PHOT routine in DAOPHOT. Although this
technique has the benefit of computational simplicity, colors derived in this manner are susceptible to stochastic variations in the spatial distribution of the brightest giants, an effect which will be exacerbated in the near-infrared. Consequently, a second set of color profiles were computed using the technique described by Piotto et al. (1988), in which each annulus is divided into eight azimuthal segments, and the median of the various segment colors is adopted as that for the annulus.

The resulting measurements, especially those for small apertures, are sensitive to the adopted location of the cluster centers, which were determined in the current study by locating the symmetry points of the cluster light distributions about the observed $x$ and $y$ axes. The results may be biased by stochastic effects in the distribution of bright giants. To remove this potential source of error, cluster centers were determined from $J$ images that were smoothed with a running boxcar median filter to suppress bright stars. The centroiding accuracies achieved with this technique are on the order ±0.5 arcsec.

The color measurements, which are summarised in Tables 5 (NGC5946) and 6 (NGC7099), are plotted in Figure 8. The errors listed in Tables 5 and 6 reflect uncertainties due to cluster centering, which is assumed to be ±0.5 arcsec, and the $K$ sky level. The former are most significant at small radii, while the latter dominate at large radii. The colors derived using the Piotto et al. (1988) technique are systematically bluer than those computed from direct aperture measurements. This result is not unexpected, as the median
filter rejects those areas containing the brightest (and reddest) giants.

The direct aperture measurements reveal a color gradient in NGC7099, and the amplitude of this gradient does not change significantly when colors are measured using the Piotto et al. (1988) technique. A least squares linear fit to the data in Table 6 indicates that $\Delta(J - K)/\Delta\log(r) = 0.09 \pm 0.02$ (aperture measurements) and $0.05 \pm 0.01$ (segmental median measurements). The quoted uncertainties reflect only the scatter in the data points for the adopted cluster centers. To estimate the uncertainty in the slopes due to centering errors, aperture measurements were made with the cluster center shifted by $\pm 0.5$ arcsec along each axis, and the resulting slopes have a standard deviation of 0.02 units. As for NGC5946, least squares linear fits to the measurements for this cluster indicate that $\Delta(J - K)/\Delta\log(r) = -0.01 \pm 0.04$ (aperture measurements) and $-0.13 \pm 0.01$ (segmental median measurements). The uncertainties in these slopes due to centering errors is comparable to that in NGC7099. The measurements made with the Piotto et al. (1988) technique suggest that a significant color gradient is seen in NGC5946; however, the sense of this gradient is opposite to that in NGC7099.

IV. COMPARISONS WITH OTHER CLUSTERS

4.1: RGB Morphology

The slope of the upper giant branch is sensitive to metallicity, in the sense that metal-poor systems have the steepest sequences. The use of giant branch morphology to determine metallicity requires a well-defined CMD
and knowledge of cluster distance — quantities which, for many clusters at low latitudes, can only be obtained in the infrared. In the following Section, the near-infrared CMD of NGC5946 is used to test the suggestion made by Alcaino et al. (1991) that this cluster is more metal-poor than $[\text{Fe/H}] \sim -1.4$.

Comparison sequences were constructed from near-infrared photometric measurements of bright giants in clusters with well-determined metallicities and reddenings, using data tabulated by Cohen et al. (1978) and Frogel, Persson, & Cohen (1983). A very metal-poor (ie. $[\text{Fe/H}] \sim -2$) giant branch sequence was constructed from observations of stars in the clusters NGC 4590 (M68), 5024 (M53), 6341 (M92), and 7078 (M15), while a corresponding moderately metal-poor (ie. $[\text{Fe/H}] \sim -1.3$) sequence was derived from the clusters NGC 362, 1261, 1851, and 2808. The individual cluster sequences were shifted to a common distance and reddening using HB brightnesses and $E(B - V)$ values listed in Table IV of Armandroff (1989); the reddening curve of Rieke & Lebofsky (1985) was used to derive $E(J - K)$ from the tabulated $E(B - V)$ values. A mean locus was then fit by hand to the composite CMD’s.

The two standard sequences are compared with the NGC5946 normal points in Figure 9. These comparisons were made using the HB brightnesses listed by Armandroff (1989), while the mean reddening of NGC5946 was allowed to vary such that each sequence matched the normal point color at $K = 12$. These comparisons reveal that if NGC5946 is very metal-poor then $E(B - V) \sim 0.60$, while if it is only moderately metal-poor then $E(B - V) \sim$
0.55. It is apparent from Figure 9 that the [Fe/H] = −2 sequence is best able to match the NGC5946 giant branch. Therefore, the claim made by Alcaino et al. (1991) that NGC5946 is more metal-poor than [Fe/H] ∼ −1.3 is supported by these data.

The integrated near-infrared colors of NGC5946 predict reddenings similar to those derived above. Using the near-infrared colors summarized in Table 5A of Brodie & Huchra (1990), if NGC5946 is very metal-poor then the unreddened color should be \((J-K)_0 = 0.58\). Hence, if \(J-K = 0.91\) (Section 3), then \(E(J-K) = 0.32\), and \(E(B-V) = 0.62\), based on the reddening curve of Rieke & Lebofsky (1985). On the other hand, if [Fe/H] = −1.3 then the intrinsic color for NGC5946 should be \((J-K)_0 = 0.66\), so that \(E(J-K) = 0.25\) and \(E(B-V) = 0.48\).

The [Fe/H] = −1.3 and −2.0 sequences are compared with the NGC7099 normal points in Figure 10. The deficiency of bright giants noted in previous studies of this cluster is readily apparent in Figure 10, and this complicates efforts to estimate metallicity from giant branch morphology, as it is the region near the RGB-tip that contains the most information concerning [Fe/H]. Nevertheless, based largely on the brightest normal point, the most metal-poor sequence gives the best match to the observations, as expected based on existing metallicity estimates (Section 1).

4.2: The Distance to NGC5946

Contamination from disk stars complicates efforts to measure the bright-
ness of the HB in low-latitude clusters, while spatial variations in reddening make corrections for selective absorption uncertain at optical wavelengths. Both of these factors conspire to make the distances to many low-latitude clusters, which are usually based on the location of the HB at optical wavelengths, highly uncertain. These errors in distance propagate into metallicity estimates derived from the CMD. Hence, it is desireable to check individual cluster distances using another standard candle.

How reliable is the HB distance for NGC5946? Liller (1983) discusses photographic photometry of six RR Lyrae variables which, based on their location within the tidal radius, are thought to be cluster members. However, a number of variables have been discovered outside the tidal radius, so it is likely that at least some of the ‘cluster’ variables are actually field stars. In fact, the CMD constructed by Alcaino et al. (1991) shows only a handful of stars in the instability strip, for which $V \sim 17.2$. The use of such a small sample of stars may produce a distance susceptible to systematic errors arising from differential reddening.

The brightness of the RGB-tip can be used to derive independent distances to globular clusters. The RGB-tip is a potentially powerful distance indicator since (1) the calibration is well-defined, with a dispersion of $\pm 0.2$ magnitudes (Frogel, Cohen, & Persson 1983); (2) RGB-tip stars are very bright, and hence easier to identify and less prone to field star contamination than, for example, HB stars; and (3) the technique can be applied in the near-infrared, where the effects of reddening are much smaller than at opti-
cal wavelengths. Nevertheless, the RGB-tip does not provide a panacea for the cluster distance scale. For example, stochastic effects are significant for low mass clusters, and this problem can only be avoided by restricting the procedure to clusters that are moderately bright. Moreover, some dynamically evolved clusters, such as NGC7099, show a central deficiency of bright giants, although these objects are identifiable based on the radial distribution of bright giants (e.g. Djorgovski & Piotto 1992). Finally, the presence of asymptotic giant branch (AGB) stars may confuse efforts to measure the brightness of the RGB-tip. However, it appears that the AGB does not extend above the RGB-tip in metal-poor clusters (e.g. Frogel 1983), so contamination from highly-evolved stars should not be an issue if applied only to clusters with $[\text{Fe/H}] \leq -1$.

In the present study, near-infrared photometric measurements of bright giants in the clusters NGC4590, 5024, 6341, and 7078 listed by Cohen et al. (1978) and Frogel, Persson, & Cohen (1983) are used to derive an empirical calibration for the RGB-tip brightness in metal-poor systems. The $K$ brightnesses of the most luminous RGB stars observed in these clusters, based on a distance scale with $M_{V}^{HB} \sim 0.6$, are summarized in Table 7. There is reasonable cluster-to-cluster agreement, and these data suggest that the RGB-tip in very metal-poor clusters is $M_{K} \sim -5.5 \pm 0.1$, where the uncertainty is the standard error of the mean. The brightest giants in NGC5946 have $K \sim 9.4$; hence, if $E(B - V) = 0.6$, then the distance modulus inferred from the RGB-tip is 14.7. For comparison, if $V_{HB} = 17.2$ (Alcaino et al.
1991), \( E(B - V) = 0.6 \), and \( M_{V}^{HB} = 0.6 \) then \( \mu_{0} = 14.7 \), in good agreement with that derived from the RGB-tip. This consistency suggests that the comparisons in Section 4.1 were made using the correct relative cluster distances, and indicates that the brightness of the RGB-tip may be useful as a distance indicator for clusters that are heavily reddened and/or subject to severe foreground star contamination.

4.3: Radial Changes in Stellar Content

The ratio of bright giants to HB stars changes with radius in NGC7099 (Alcaino & Wamsteker 1982; Buonanno et al. 1988; Djorgovski & Piotto 1992), and recent observations with the HST have detected a centrally concentrated population of blue stragglers (Yanny et al. 1994). Given the evidence for radial changes in stellar content, it is not surprising that broad-band color gradients at optical wavelengths have been detected (e.g. Cordoni & Auriere 1984; Pastoriza et al. 1986; and Piotto, King, & Djorgovski 1988), and the amplitude of these gradients are similar to those seen in other dynamically evolved clusters (e.g. Djorgovski et al. 1991).

The data presented here reveal that the near-infrared color of NGC7099 changes with radius. The rate with which \( J - K \) changes with \( \log(r) \) in NGC7099 is insensitive to the technique used to measure color, suggesting that the gradients are not caused exclusively by the brightest giant branch stars, which the Piotto et al. (1988) technique suppresses. The detection of near-infrared color gradients in NGC7099 and NGC4147 (Davidge 1992)
suggests that similar radial changes in $J-K$ might be expected in NGC5946. It is therefore interesting that, despite having a post core-collapse morphology, the current data fail to detect $J-K$ variations in NGC5946 similar to those in NGC7099 — in fact, NGC5946 appears to contain a gradient in the opposite sense to that seen in other post core-collapsed clusters. NGC5946 is the only post core-collapse cluster studied to date to show this behaviour (e.g. Djorgovski & Piotto 1992). It could be argued that differential reddening may mask an underlying color gradient. However, this is unlikely as the width of the giant branch indicates that differential reddening is at most $\pm 0.04$ mag in $J-K$ (Section 3), and aperture measurements, especially those which utilize median filtering techniques, will act to suppress reddening differences over moderately large spatial scales.

Studies of the spatial distribution of bright giants at near-infrared wavelengths provide a means of investigating the radial stellar content of clusters in a manner that is largely independent of differential reddening. Djorgovski & Piotto (1992) found an absence of bright giants within 10 arcsec of the center of NGC7099. The spatial distributions of bright giants in NGC7099 derived from the current data is examined in the two right hand panels of Figure 11, where the CMD’s of stars in annuli within the intervals 0–10 and 10–19 arcsec are compared. These intervals have comparable integrated $K$ brightnesses, so they should contain similar numbers of stars. In an effort to quantify the spatial distribution of bright giants, the number of stars detected within 2 magnitudes in $K$ of the RGB-tip, as derived using the
calibration in Section 4.2, were counted. In the particular case of NGC7099, the RGB-tip should occur at $K = 9.0$, so the number of stars brighter than $K = 11$ in each radial interval provide the relevant data. It is evident that whereas 4 stars are seen with $K \leq 11$ in the outer annulus, only 1 star with this brightness is seen in the inner annulus.

The radial distribution of bright giants in NGC5946 is investigated in the two left hand panels of Figure 11. Annuli were selected for NGC5946 that sample the same intervals in linear units as in NGC7099, and these have inner-outer radii of $0 - 9$ arcsec and $9 - 16.5$ arcsec after adjusting for the difference in distance. In both intervals there are 5 stars within 2 magnitudes of the RGB-tip ($K = 9.5$), so there is no evidence for radial changes in the number of bright giants. This result provides further evidence that NGC5946 does not contain population gradients like those in NGC7099, even though it is a post core-collapse cluster. It would be of interest to survey a larger sample of dynamically evolved low-latitude globular clusters at infrared wavelengths to determine what fraction of these objects contain radial gradients in stellar content like those seen in NGC7099.

V. SUMMARY

The results presented in this paper demonstrate that near-infrared measurements can be used to study the metallicities, distances, and radial stellar contents of heavily reddened globular clusters. The specific conclusions of this study are:
1) The upper giant branch of NGC5946 in the \((K, J-K)\) diagram is relatively steep, indicating that the metallicity is significantly lower than \([\text{Fe/H}] \sim -1.4\). If NGC5946 is as metal-poor as the giant branch slope indicates, then \(E(J-K) = 0.3\), which corresponds to \(E(B-V) = 0.6\) using the reddening curve of Rieke & Lebofsky (1985).

2) The color and slope of the RGB in the \((K, J-K)\) diagram of NGC7099 is consistent with the metal-poor nature of this cluster. There is a deficiency of giants within 2 mag in \(K\) of the giant branch tip in the central regions of this cluster, consistent with earlier observations at optical wavelengths.

3) The distance modulus of NGC5946 derived from the brightness of the RGB-tip is 14.7. This estimate, which assumes that \(M_{V}^{HB} = 0.6\) in very metal-poor clusters, is in excellent agreement with that derived from the visual brightness of the HB if \(E(B-V) = 0.6\).

4) NGC7099 contains near-infrared color gradients with slope \(\Delta(J-K)/\Delta \log(r) \sim 0.05-0.1\), depending on the technique used to measure color. Both bright giants and fainter stars appear to be responsible for the observed near-infrared color variations.

5) Although NGC5946 shows a highly concentrated light profile suggestive of dynamical evolution, neither the integrated \(J-K\) color nor the specific frequency of bright giant branch stars varies with radius out to a distance of 30 arcsec from the cluster center. If colors are measured using the technique described by Piotto et al. (1988) then a color gradient is detected, but the
sense of this gradient is opposite to what is seen in NGC7099 and other post core-collapsed clusters.

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TABLE 1. Observing Log

| Cluster    | Date (UT)     | Field # | Filter | Exposure time (sec) | Seeing (arcsec) |
|------------|---------------|---------|--------|---------------------|-----------------|
| NGC5946    | February 1, 1994 | 1       | J      | 3 x 20              | 1.2             |
|            |               |         | H      | 3 x 20              | 1.2             |
|            |               |         | K      | 6 x 20              | 1.2             |
| NGC5946    | February 1, 1994 | 2       | J      | 12 x 100            | 1.2             |
|            |               |         | K      | 54 x 50             | 1.2             |
| NGC7099    | May 26, 1991   | 1       | J      | 3 x 20              | 1.0             |
|            |               |         | K'     | 3 x 45              | 1.0             |
TABLE 2. NGC5946 Stars with $V$, $J$, and $K$ measurements

| n$^a$ | $K$  | $J - K$ | $V - K$ |
|-------|------|--------|--------|
| 96    | 14.44| 0.47   | 2.62   |
| 174   | 12.66| 1.08   | 4.43   |
| 268   | 13.67| 0.87   | 3.42   |
| 176   | 12.72| 0.83   | 3.79   |
| 163   | 12.89| 0.88   | 3.76   |
| 271   | 13.97| 0.76   | 5.26   |
| 170   | 12.88| 0.79   | 3.91   |
| 186   | 13.29| 0.80   | 3.92   |
| 165   | 14.87| 0.46   | 2.41   |
| 156   | 13.74| 0.79   | 4.09   |
| 149   | 15.14| 0.46   | 2.35   |
| 124   | 13.50| 0.88   | 4.16   |
| 92    | 13.91| 0.83   | 2.77   |
| 77    | 14.42| 0.62   | 2.77   |
| 65    | 14.44| 0.63   | 2.70   |
| 66    | 14.33| 0.24   | 2.19   |
| 81    | 13.33| 0.80   | 3.64   |
| 120   | 10.79| 0.93   | 4.20   |
| 141   | 12.73| 0.84   | 4.10   |
| 162   | 10.37| 1.03   | 4.60   |
| 171   | 11.68| 0.96   | 4.14   |
| 193   | 11.94| 0.94   | 4.16   |
| 143   | 9.30 | 1.11   | 4.84   |
| 148   | 11.80| 0.91   | 4.29   |
| 182   | 12.40| 0.89   | 4.16   |

$^a$ Identification number from Alcaino et al. (1991).
| $n^a$ | $K$  | $J - K$ | $V - K$ |
|------|------|---------|---------|
| 131  | 11.88| 0.89    | 4.23    |
| 116  | 11.88| 0.93    | 4.19    |
| 97   | 10.98| 0.11    | 0.91    |
| 79   | 11.37| 0.88    | 4.04    |
| 80   | 11.81| 0.85    | 3.86    |
| 83   | 12.86| 0.78    | 4.19    |
| 75   | 11.97| 0.83    | 3.98    |
| 115  | 10.27| 0.99    | 4.54    |

$^a$ Identification number from Alcaino et al. (1991).
TABLE 3. NGC7099 Stars with $V$, $J$, and $K$ measurements

| $n^a$ | $K$  | $J - K$ | $V - K$ |
|-------|------|---------|---------|
| 17    | 14.43| 0.17    | 0.59    |
| 19    | 12.84| 0.59    | 2.21    |
| 23    | 13.80| 0.25    | 1.03    |
| 24    | 13.04| 0.59    | 1.84    |
| 32    | 10.51| 0.65    | 2.70    |
| 28    | 11.73| 0.64    | 2.46    |
| 25    | 11.79| 0.60    | 2.30    |
| 18    | 14.33| 0.14    | 0.52    |
| 6     | 12.25| 0.60    | 2.23    |
| 5     | 12.26| 0.64    | 2.27    |
| 4     | 11.83| 0.64    | 2.31    |
| 27    | 10.63| 0.63    | 2.60    |
| 26    | 10.64| 0.69    | 2.66    |
| 29    | 12.87| 0.55    | 2.11    |
| 30    | 11.58| 0.59    | 2.41    |
| 31    | 12.24| 0.58    | 2.27    |
| 40    | 12.04| 0.61    | 2.32    |
| 41    | 12.04| 0.64    | 2.40    |
| 42    | 14.39| 0.17    | 0.48    |
| 44    | 12.13| 0.57    | 2.18    |
| 45    | 14.99| 0.05    | 0.17    |
| 43    | 12.00| 0.61    | 2.23    |
| 67    | 10.35| 0.66    | 2.57    |
| 47    | 14.99| -0.03   | 0.16    |
| 65    | 13.21| 0.44    | 1.71    |

$a$ Identification number from Alcaino & Liller (1980).
TABLE 3. (con’t)

| n  | $K$  | $J - K$ | $V - K$ |
|----|------|---------|---------|
| 49 | 13.97| 0.39    | 1.14    |
| 66 | 12.63| 0.57    | 2.23    |
| 63 | 12.73| 0.66    | 2.17    |
| 64 | 10.88| 0.67    | 2.62    |
| 62 | 10.33| 0.71    | 2.79    |
| 61 | 12.74| 0.53    | 2.16    |
| 70 | 12.61| 0.60    | 2.21    |
| 73 | 11.90| 0.58    | 2.22    |
| 72 | 12.55| 0.60    | 2.23    |
| 74 | 12.08| 0.63    | 2.34    |
| 75 | 11.27| 0.61    | 2.54    |
| 71 | 12.77| 0.57    | 2.09    |
| 77 | 10.48| 0.67    | 2.71    |
| 76 | 14.54| 0.15    | 0.43    |

$^a$ Identification number from Alcaino & Liller (1980).
| $K$ | $(J - K)_{5046}$ | $(J - K)_{7099}$ |
|-----|----------------|-----------------|
| 9.5 | 1.09           | –               |
| 10.0| 1.00           | 0.64            |
| 10.5| 1.00           | 0.66            |
| 11.0| 0.94           | 0.63            |
| 11.5| 0.91           | 0.58            |
| 12.0| 0.90           | 0.59            |
| 12.5| 0.87           | 0.57            |
| 13.0| 0.84           | 0.56            |
| 13.5| 0.82           | 0.53            |
| 14.0| 0.79           | 0.51            |
| 14.5| –              | 0.50            |
| 15.0| –              | 0.48            |
| 15.5| –              | 0.45            |
TABLE 5. NGC5946 Color Measurements

| Radius (arcsec) | \((J - K)^a\) | \((J - K)^b\) | Error    |
|----------------|--------------|--------------|----------|
| 0.5            | 0.88         | 0.94         | ±0.04    |
| 1.4            | 0.90         | 0.88         | ±0.05    |
| 2.8            | 0.92         | 0.84         | ±0.05    |
| 5.6            | 0.88         | 0.78         | ±0.06    |
| 11.3           | 0.96         | 0.78         | ±0.08    |
| 22.6           | 0.84         | 0.71         | ±0.30    |

\(^a\) Color from direct aperture measurement.

\(^b\) Color derived from scheme discussed by Piotto et al. (1988).
TABLE 6. NGC7099 Color Measurements

| Radius (arcsec) | \((J - K)^a\) | \((J - K)^b\) | Error  |
|----------------|---------------|---------------|--------|
| 0.4            | 0.39          | 0.34          | ±0.05  |
| 1.1            | 0.46          | 0.36          | ±0.05  |
| 2.2            | 0.45          | 0.40          | ±0.05  |
| 4.4            | 0.53          | 0.38          | ±0.06  |
| 8.9            | 0.49          | 0.41          | ±0.12  |
| 17.8           | 0.55          | 0.43          | ±0.23  |

\(a\) Color from direct aperture measurement.

\(b\) Color derived from scheme discussed by Piotto et al. (1988).
TABLE 7. The Brightest Giants in Metal-Poor Clusters

| Cluster | Star | $K$ | $M_K^{I_{BP}}$ |
|---------|------|-----|---------------|
| NGC4590 | I-260 | 9.52 | −5.40         |
| NGC5024 | IR-1 | 10.61 | −5.73        |
| NGC6341 | III-13 | 8.93 | −5.47        |
| NGC7078 | I-12 | 9.42 | −5.56        |
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FIGURE CAPTIONS

FIG. 1. Final $K$ image of NGC5946 Field 1. The dimensions of this image are roughly $90 \times 93$ arcsec.

FIG. 2. Final $K$ image of NGC5946 Field 2. The dimensions of this image are roughly $83 \times 81$ arcsec.

FIG. 3. Final $K'$ image of NGC7099 field. The image dimensions are roughly $75 \times 94$ arcsec.

FIG. 4. ($K, J-K$) CMD's of, from left to right, NGC5946 Field 1, NGC5946 Field 2, and NGC7099. Only stars with errors from ALLSTAR $\leq 0.07$ mag have been included in this figure.

FIG. 5. ($K, V-K$) CMD's of NGC5946 Field 1 (left hand side) and NGC7099 (right hand side). The $V$ measurements are those given by Alcaino et al. (1991 – NGC5946) and Alcaino & Liller (1980 – NGC7099).

FIG. 6. The $J, H, H-K$ two-color diagram for stars in NGC5946 Field 1 with $K \leq 13$. Also shown are bright stars in M13 (open squares) and M92 (filled squares) from Cohen et al. (1978), shifted to match the reddening of NGC5946. The solid line is the locus of solar neighborhood giants from Bessell & Brett (1988), also shifted to match the reddening of NGC5946.

FIG. 7. The $J-K, V-K$ two-color diagram for stars in NGC5946 (top
panel) and NGC7099 (bottom panel). Also shown are bright giants in M13
(open squares) and M92 (filled squares) from Cohen et al. (1978), as well
as the locus of solar neighborhood giants from Bessell & Brett (1988 — solid
line). The M13, M92, and solar neighborhood data have been shifted to
match the reddenings of NGC5946 and NGC7099.

FIG. 8. The $J - K$ color profiles for NGC5946 (open squares) and NGC7099
(filled squares). Colors resulting from direct aperture measurements are
shown in the top panel, while those made using the segmental median tech-
nique of Piotto et al. (1988 — see text) are shown in the lower panel.

FIG. 9. NGC5946 Field 1 normal points (crosses) compared with [Fe/H] = −2 (left hand panel) and [Fe/H] = −1.3 cluster sequences (right hand panel).

FIG. 10. NGC7099 normal points (crosses) compared with [Fe/H] = −2 (left
hand panel) and [Fe/H] = −1.3 cluster sequences (right hand panel).

FIG. 11. CMD’s for stars in NGC5946 and NGC7099 falling within various
distances from the cluster centers. The CMD’s for NGC5946 sample the
intervals 0 — 9 (upper left hand corner) and 9 — 16.5 (lower left hand corner)
arcsec. The CMD’s for NGC7099 sample the regions 0 — 10 (upper right
hand corner) and 10 — 19 (lower right hand corner) arcsec.

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