HIGH ANGULAR RESOLUTION JHK IMAGING OF THE CENTERS OF THE METAL-POOR GLOBULAR CLUSTERS NGC 5272 (M3), NGC 6205 (M13), NGC 6287, AND NGC 6341 (M92)

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ABSTRACT

The Canada-France-Hawaii Telescope Adaptive Optics Bonnette has been used to obtain high angular resolution JHK images of the centers of the metal-poor globular clusters NGC 5272 (M3), NGC 6205 (M13), NGC 6287, and NGC 6341 (M92). The color-magnitude diagrams (CMDs) derived from these data include the upper main sequence and most of the red giant branch and agree with published photometric measurements of bright stars in these clusters. The photometric accuracy is limited by point-spread function variations, which introduce systematic errors of a few hundredths of a magnitude near the reference star. The NGC 6287 CMDs are of particular interest, as they are free of the scatter caused by foreground stars and differential reddening that have plagued previous efforts to study the stellar content of this inner spheroid cluster. The horizontal branch (HB) of NGC 6287 contains stars spanning a broader range of temperatures than that of NGC 6341. NGC 6287 is thus the only known member of the metal-poor inner spheroid to deviate from the HB morphology versus metallicity relation defined by other clusters in the inner Galaxy.

The clusters are paired according to metallicity, and the near-infrared CMDs and luminosity functions are used to investigate the relative ages within each pair. The near-infrared CMDs provide the tightest constraints on the relative ages of the classical second-parameter pair NGC 5272 and NGC 6205 and indicate that these clusters have ages that differ by no more than ±1 Gyr. These results thus support the notion that age is not the second parameter. We tentatively conclude that NGC 6287 and NGC 6341 have ages that differ by no more than ±2 Gyr. However, the near-infrared spectral energy distributions of stars in NGC 6287 appear to differ from those of stars in outer halo clusters, bringing into question the validity of this age estimate.

Key words: globular clusters: individual (NGC 5272, NGC 6205, NGC 6287, NGC 6341) — infrared: stars

1. INTRODUCTION

Deep photometric studies of globular clusters have traditionally been restricted to the less crowded outer regions of these objects. Although surveys of this nature with electronic detectors have permitted the properties of relatively faint main-sequence stars in nearby clusters to be studied in detail, it has been difficult to assemble photometry of statistically significant samples of stars in the more advanced stages of evolution using the same instrumentation. The extent of this problem can be reduced by observing the central regions of clusters, where the high stellar densities simplify efforts to obtain photometry of stars spanning a range of brightnesses and evolutionary phases, including the brightest portions of the red giant branch (RGB). Studies of the central regions of clusters also reduce the effects of foreground star contamination and, especially when conducted at infrared wavelengths, differential reddening, both of which frustrate efforts to probe the nature of low-latitude clusters—objects that will provide important clues into the early evolution of the inner Galaxy.

The cost of observing stars in these high-density environments is increased crowding, and angular resolutions approaching the diffraction limits of moderately large telescopes are required to survey all but the brightest cluster stars.

In the current paper, high angular resolution near-infrared images obtained with the Canada-France-Hawaii Telescope (CFHT) Adaptive Optics Bonnette (AOB) are used to probe the central stellar contents in two metal-poor cluster pairs: NGC 5272 (M3) + NGC 6205 (M13) and NGC 6287 + NGC 6341 (M92). The clusters in each pair were selected to have similar metallicities and distances to facilitate differential photometric comparisons. The basic properties of the target clusters, including [Fe/H], E(B − V), distance from the Galactic center, R_GC, the V brightness of the horizontal branch (HB) corrected for reddening, V^HB, the central surface brightness in V corrected for reddening, μ^0_V, and the integrated cluster brightness, M_V, are summarized in Table 1. The data in this table were taken from the 1997 May 15 version of the Harris (1996) database; the reddening corrections assume that A_V/E(B − V) = 3.1.

The clusters NGC 5272 and NGC 6205, which are a classical second-parameter pair, have been the subject of numerous photometric and spectroscopic investigations at visible wavelengths. However, only a modest body of infrared photometric data has previously been obtained for these clusters. Cohen, Frogel, & Persson (1978) recorded deep photometric measurements of selected bright giants in the outer regions of both clusters, whereas Davidge & Harris (1995a, 1995b) used moderately deep J and K images to investigate the stellar content of giants and main-sequence stars in NGC 6205.

NGC 6287 and NGC 6341 are among the most metal-poor clusters in the Galaxy. NGC 6341 has been well

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studied at visible wavelengths and is a standard benchmark for constraining the age of the universe (see, e.g., Salaris, Degl’Innocenti, & Weiss 1997; Bolte & Hogan 1995). Cohen et al. (1978) also obtained near-infrared aperture measurements of bright stars in the outer regions of this cluster. NGC 6287 is located in the inner regions of the Galaxy. The close proximity to the Galactic center, size, and metallicity of NGC 6287 lead van den Bergh (1993) to suggest that this cluster may be one of the oldest objects in the Galaxy. Efforts to interpret the visible (Stetson & West 1994) and near-infrared (David 1998) color-magnitude diagrams (CMDs) of the outer regions of NGC 6287 are complicated by differential reddening and field star contamination. David (1998) derived an age of 12 Gyr for NGC 6287 based on the K luminosity function (LF) of subgiant branch (SGB) stars and comparisons with the Bergbusch & VandenBerg (1992) models.

The data presented in this paper will be used to investigate the photometric characteristics of the cluster stars and assess relative ages within each cluster pair. The data were recorded with a single instrumental configuration over a period of only two nights and include the main-sequence turno† (MSTO); hence, these data are well suited to the task of relative age determination. The observations and reductions are described in § 2, while the photometric measurements, LFs, and CMDs are discussed in § 3. This information is used to investigate the relative ages of each pair of clusters in § 4. A summary and discussion of the results follows in § 5.

2. OBSERVATIONS AND REDUCTIONS

The data were recorded on the nights of UT 1998 March 8/9 (NGC 5272, NGC 6205, and NGC 6287) and March 9/10 (NGC 6341) with the CFHT AOB (Rigaut et al. 1998) and KIR camera. The latter contains a 1024 × 1024 Hg:Cd:Te array with an angular scale of 0”034 per pixel, so that the total imaged field is 35” × 35”.

Data were recorded through J, H, and K filters, with a complete observing sequence consisting of four exposures per filter. The exception was NGC 5272, for which eight exposures per filter were recorded. The telescope pointing offset following each exposure to de†ine a 0”03 radius was o†set following each exposure to de†ine a 0”03 radius pattern. Additional details of the observations, including right ascension (α) and declination (δ) of the field centers, total exposure times, and the FWHM of the central peak in the point-spread function (PSF), averaged over the entire field, are summarized in Table 2.

With the exception of NGC 6205, which was observed during a brief episode of bad seeing, the FWHM entries for H and K are close to the telescope diffraction limit. However, at moderate Strehl ratios the FWHM provides an incomplete picture of image quality, as much of the energy in the PSF is contained outside of the central peak (see, e.g., David et al. 1997a, 1997b); indeed, the AO-compensated PSF was traced out to a radius of at least 1”5 in observations of moderately bright stars recorded on the same nights as the cluster data. The diameter of an aperture containing 50% of the PSF energy provides a means of quantifying the light distribution, and the 50% encircled energy diameters for the NGC 6287 data, which should also be representative of the NGC 5272 and NGC 6341 observations, are 0”42 (J), 0”25 (H), and 0”25 (K).

The raw images contain signatures introduced by the telescope, instrumentation, and sky that must be removed before making photometric measurements. Some of these

| NGC     | [Fe/H] | E(B−V) | V^HM0 | R_GC (kpc) | μ^0' (mag arcsec^-2) | M_v |
|---------|--------|--------|--------|------------|----------------------|-----|
| 5272    | −1.57  | 0.01   | 15.62  | 11.9       | 16.31                | −8.85 |
| 6205    | −1.54  | 0.02   | 14.84  | 8.3        | 16.74                | −8.50 |
| 6287    | −2.05  | 0.59   | 15.17  | 1.6        | 16.50                | −7.11 |
| 6341    | −2.29  | 0.02   | 15.04  | 9.5        | 15.52                | −8.15 |

| NGC     | α (E2000) | δ (E2000) | Filter | Exposure Time (s) | FWHM (arcsec) |
|---------|-----------|-----------|--------|------------------|---------------|
| 5272    | 13 42 11.2 | +28 32 22 | J      | 8 × 30           | 0.31          |
|         |           |          | H      | 8 × 30           | 0.14          |
|         |           |          | K      | 8 × 30           | 0.14          |
| 6205    | 16 41 39.9 | +36 27 36 | J      | 4 × 90           | 0.29          |
|         |           |          | H      | 4 × 90           | 0.26          |
|         |           |          | K      | 4 × 90           | 0.22          |
| 6287    | 17 05 09.3 | −22 42 27 | J      | 4 × 60           | 0.24          |
|         |           |          | H      | 4 × 60           | 0.15          |
|         |           |          | K      | 4 × 60           | 0.17          |
| 6341    | 17 15 34.4 | +43 11 01 | J      | 4 × 30           | 0.22          |
|         |           |          | H      | 4 × 20           | 0.14          |
|         |           |          | K      | 4 × 15           | 0.15          |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
signatures are multiplicative in nature (throughput variations introduced by the optics and pixel-to-pixel differences in detector sensitivity), whereas others are additive (detector bias and dark current, thermal emission from objects along the optical path, and sky emission). Calibration frames monitoring these signatures were either recorded (darks, flats) or derived (thermal emission) from the observations. Dark frames for each integration time were recorded midway through the run, whereas dome flats were constructed by subtracting exposures of the dome white spot taken with the flat-field lamps "off" from those recorded with the lamps "on." This differencing procedure removes the additive contributions from detector dark current and thermal emission, while preserving the multiplicative flat-field and detector sensitivity variations. Images showing the thermal emission pattern for each filter were constructed by median-combining flat-fielded images of blank sky regions, which were recorded at various times throughout the run.

The data were reduced using the following sequence: (1) dark subtraction; (2) division by dome flats; (3) subtraction of the DC sky level, which was estimated by taking the mode of the pixel intensity distribution in each flat-fielded frame; and (4) subtraction of the thermal signature. The results for each field were registered to correct for the offsets

Fig. 1.—Final K image of the NGC 5272 field. The area covered is roughly 34'' × 34''. North is at the top, and east is to the left.
introduced while dithering and then median-combined. The final $K$ images are shown in Figures 1, 2, 3, and 4.

3. PHOTOMETRIC MEASUREMENTS

The photometric measurements were made using the PSF-fitting routine ALLSTAR (Stetson & Harris 1988), which is part of the DAOPHOT (Stetson 1987) photometry package. Anisoplanaticism causes the PSF to vary with distance from the AO reference star, and the extent of these variations in the NGC 6287 field is illustrated in Figure 5, where the $J$ and $K$ PSFs in two different annuli centered on the reference star are compared. The effects of anisoplanaticism are greatest in $J$, where the FWHM changes from 0.18 to 0.28 between the inner and outer annuli. For comparison, the FWHM changes from 0.12 and 0.14 in $K$.

PSF variations complicate efforts to measure accurate stellar brightnesses. To quantify the affects of PSF variations in the current data, stellar brightnesses were measured from the NGC 6287 $J$ and $K$ images using PSFs constructed from stars (1) distributed over the entire field; (2) when the distance between a star and the reference source, is $\leq 8.5$; and (3) when $r_0 \geq 8.5$.

The brightnesses of stars with $r_0 \geq 8.5$ measured with the first and third set of PSFs are very similar, indicating that the use of a constant PSF does not significantly affect photometric measurements at moderately large distances.

Fig. 2.—Same as Fig. 1, but for NGC 6205
from the reference star. The mean brightness differences among moderately bright stars when using these PSFs are $\Delta_{13} = 0.01 \pm 0.03$ mag ($J$) and $0.02 \pm 0.03$ mag ($K$), where the quoted errors are dominated by uncertainties in the aperture corrections. The standard deviations about the $\Delta_{13}$ values provide additional insight into the affects of PSF variations, and these are $\sigma_{13} = 0.003$ mag ($J$) and 0.001 mag ($K$). This comparison indicates that the use of a PSF constructed from stars over the entire field affects brightness measurements by $\sim 0.01$ mag when $r_0 \geq 8.5$. Roughly 80% of the stars in our sample are located in this region.

PSF variations are of greater concern close to the reference source. Indeed, the mean brightness differences between measurements made with the first and second set of PSFs for stars with $r_0 \leq 8.5$ are $\Delta_{12} = -0.07 \pm 0.14$ (J) and $-0.10 \pm 0.06$ (K). The errors reflect the large uncertainties in the aperture corrections for the measurements made using the second set of PSFs, as the number of PSF stars is small when $r_0 \leq 8.5$, and there is significant crowding, as the reference source is located close to the cluster center. The standard deviation about the $\Delta_{12}$ values are $\sigma_{12} = 0.03$ mag ($J$) and 0.01 mag ($K$). Hence, PSF variations affect brightness measurements near the reference source by a few hundredths of a magnitude. We emphasize that only 20% of the stellar sample is located within 8.5 of the reference source.
The PSF variations introduced by anisoplanaticism depend on a number of environmental (e.g., wind speed and direction, altitude distribution of turbulence layers, location and brightness of the reference source, etc.) and instrumental (e.g., the alignment of optical components and the detector, order of compensation provided by the AO system, etc.) factors and, with the limited environmental information currently available at most telescopes, can only be modeled empirically. Although DAOPHOT has the capability of constructing a variable PSF, a large number of bright, preferably isolated, stars are required, and efforts to construct a variable PSF that produced better photometric measurements than a single PSF, constructed from stars over the entire field for each cluster + filter combination, were confounded by crowding. Given these difficulties, and also considering that the experiments described above indicate that the majority of stars are not affected by the use of a constant PSF, we elected to use a single PSF to obtain photometric measurements for subsequent analysis.

The photometric calibration was defined using UKIRT faint standard stars (Casali & Hawarden 1992), which were observed at various times throughout the two-night run. The standard star brightnesses were corrected for atmospheric extinction using the coefficients derived by Guarneri, Dixon, & Longmore (1991), and the results were then used to derive photometric zero points and first-order color
that the data are complete to \( K \) stars per 0.5 mag interval per square arcsecond. It is evident that the brightnesses at which sample incompleteness begins to be significant can be estimated from the turnover points at the faint end of the LFs. The \( K \) LFs of these clusters are plotted in Figure 6, where \( n_{0.5} \) is the number of stars per 0.5 mag interval per square arcsecond. It is evident that the data are complete to \( K = 18\text{--}19 \) mag, which is comparable to, or slightly fainter than, the MSTO in each cluster.

The \((H, J-H)\), \((K, H-K)\), and \((K, J-K)\) CMDs are plotted in Figures 7, 8, and 9. The RGB, SGB, MSTO, and HB sequences are clearly evident in the \((H, J-H)\) and \((K, J-K)\) CMDs of all four clusters; an asymptotic giant branch (AGB) component is also apparent in the NGC 5272, NGC 6205, and NGC 6287 CMDs. The NGC 5272 CMDs involving the \( J \) filter show the largest photometric scatter, as these data have unusually large PSF variations. However, the scatter in the other CMDs is modest, and this is demonstrated in Figure 10, where the \( H-K \) color distributions of stars with \( K \) between 12 and 14.5, an interval over which the \((K, H-K)\) CMD is practically vertical and contamination from the HB is small, are shown. The standard deviations of these distributions range from a low of \( \pm 0.023 \) mag for NGC 6205 to a high of \( \pm 0.046 \) mag for NGC 5272. If the random uncertainties in the \( H \) and \( K \) measurements are assumed to be equal, then these comparisons suggest that the internal photometric errors in the \( H \) and \( K \) measurements of moderately bright stars are \( \pm 0.016 \) mag for NGC 6205 and \( \pm 0.033 \) mag for NGC 5272. Two caveats that should be considered when assessing these results are that (1) the presence of AGB stars will broaden the distributions slightly and (2) the PSF-variation experiments described earlier indicate that the widths of the color distributions are lower limits that apply mainly to stars more than 8\text{.}5\text{'} from the reference source.

Comparisons with published infrared photometric measurements verify the color calibration of the AOB data. The open squares in Figures 7, 8, and 9 are the single-element detector measurements published by Cohen et al. (1978) for bright giants in NGC 5272, NGC 6205, and NGC 6341 and the array detector measurements published by Davidge (1998) of bright stars near the center of NGC 6287. Crowding and, to a lesser extent, differential reddening cause the scatter in the Davidge (1998) measurements to be larger than in the Cohen et al. measurements, which are restricted to stars in the outer regions of the clusters. It is evident that the published data are in reasonable agreement with the AOB observations.

The brightnesses and colors of key features on the CMDs that provide age and distance information at infrared wavelengths have been measured, and the results are listed in Table 3. The brightness of the HB is the standard means of judging cluster distances at visible wavelengths. However, the HB is not considered here because (1) it forms an almost vertical sequence on infrared CMDs, and (2) whereas relations between RR Lyrae infrared brightness and period have been defined (see, e.g., Carney, Storm, & Jones 1992; Longmore et al. 1990), NGC 6287 has not yet been extensively surveyed for variable stars. Therefore, the brightness of the RGB tip is adopted to gauge relative distances. Stochastic effects may compromise RGB tip brightness measurements because evolution on the upper giant branch proceeds at a rapid pace. However, numerical simulations indicate that only a modest survey of bright stellar content is required to determine the RGB tip brightness to an accuracy of \( \pm 0.1 \) mag in a typical globular cluster (Crocker & Rood 1984).

Stars near the RGB tip are saturated in the AOB data. Therefore, the \( J, H \), and \( K \) brightnesses of the RGB tip for NGC 5272, NGC 6205, and NGC 6341 were estimated from the brightest stars in the Cohen et al. (1978) sample.
These same Cohen et al. (1978) measurements were considered by Frogel, Cohen, & Persson (1983) in their study of the bolometric brightness of the RGB tip in a much larger sample of globular clusters, and the RGB tip brightnesses derived for NGC 5272, NGC 6205, and NGC 6341 fell within the ±0.1 mag scatter envelop defined by the larger cluster sample, lending confidence to the RGB tip brightness estimates for these three clusters. Davidge (1998) measured the K brightness of the RGB tip for NGC 6287, and RGB tip brightnesses in J and H were obtained from the data listed in Table 3 of that paper. The RGB tip brightnesses listed in Table 3 of the current paper have an estimated uncertainty of ±0.1 mag.

RGB tip brightnesses can be used to estimate absolute distances, although the calibration is very uncertain. The Bergbusch & VandenBerg (1992) isochrones, when transformed onto the near-infrared observational plane using the color relations given by Davidge & Harris (1995a), predict that $M_K = -5.9$ for metal-poor clusters, so that the predicted distance moduli for the clusters are 15.1 (NGC 5272), 14.3 (NGC 6205), 14.6 (NGC 6287), and 14.8 (NGC 6341). For comparison, the Bertelli et al. (1994) models predict an RGB tip brightness that is 0.2 mag fainter in K. The resulting distance moduli are reasonably consistent with those predicted by the Carney et al. (1992) RR Lyrae calibration, which gives distance moduli of 14.9 (NGC 5272), 14.1 (NGC 6205), and 14.4 (NGC 6341) with the cluster properties given in Table 1.

Although the brightness of the MSTO is a prime age indicator, it cannot be measured accurately from these data.

| NGC  | $(J-H)_{\text{MSTO}}$ | $(J-K)_{\text{MSTO}}$ | $J_{\text{SGB}}$ | $H_{\text{RGB}}$ | $K_{\text{SGB}}$ | $J_{\text{RGB}}$ | $H_{\text{RGB}}$ | $K_{\text{RGB}}$ |
|------|----------------------|----------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 5272 | 0.239 | 0.234 | 16.56 | 16.22 | 16.63 | 10.08 | 9.29 | 9.16 |
| 6205 | 0.225 | 0.290 | 16.28 | 16.06 | 16.17 | 9.32 | 8.60 | 8.49 |
| 6287 | 0.461 | 0.774 | 16.62 | 16.33 | 15.98 | 10.18 | 9.25 | 9.00 |
| 6341 | 0.210 | 0.230 | 16.10 | 15.86 | 16.09 | 9.69 | 9.05 | 8.93 |

Note.—The errors in the MSTO colors are ±0.03 mag. The estimated uncertainty in the SGB and RGB tip brightnesses is ±0.1 mag.
as the CMDs are almost vertical at this point. However, the brightness of the SGB provides age information that is comparable to that of the MSTO brightness (Chaboyer et al. 1996). For this study the SGB brightness 0.1 mag redward of the MSTO was measured from the ridge line of each CMD, and the estimated uncertainty in these measurements is ±0.1 mag. The $J - H$ and $J - K$ colors of the MSTO are very well-defined, and the estimated uncertainties in the observed MSTO colors are ±0.03 mag.

The dereddened MSTO colors for each cluster, derived using the Rieke & Lebofsky (1985) reddening law, are listed in Table 4. The MSTO colors for NGC 6341 are the smallest of the group, as expected given that this is the most metal-poor cluster. However, the dereddened MSTO colors of NGC 6287 are abnormally large, especially in $J - K$. It is worth noting that the uncertainty in $E(B - V)$ for NGC 6287 is relatively large, amounting to 0.1–0.2 mag. $E(B - V)$ estimates for this cluster derived from data at visible wavelengths favor a value near 0.6 (Zinn 1980; Reed, Hesser, & Shawl 1988; Stetson & West 1994), whereas far-infrared properties of interstellar dust (Schlegel, Finkbeiner, & Davis 1998) and the near-infrared colors of giant branch stars (Davidge 1998) favor 0.8. Nevertheless, even if $E(B - V) = 0.8$ (Davidge 1998), then $(J - K)_{\text{MSTO}} = 0.34$, which is still significantly larger than the other clusters, although $(J - H)_{\text{MSTO}} = 0.19$ in this case.

The MSTO colors of NGC 6287 ostensibly suggest that either (1) the near-infrared reddening law toward this

![Figure 8](image-url)
cluster differs significantly from that given by Rieke & Lebofsky (1985) or (2) the spectral energy distribution (SED) of stars in this cluster is somehow peculiar. The \((J - H, H - K)\) two-color diagram (TCD) provides additional insight into these possibilities, and the TCD for each cluster is shown in Figure 11. In an effort to reduce observational scatter, normal points were created by computing the mode of the color distribution in \(\pm 0.25\) mag (RGB) or \(\pm 0.1\) mag (SGB, MSTO) bins along the \(K\)-axis of the CMDs in Figures 8 and 9, and it is the resulting \(J - H\) and \(H - K\) pairs for each \(K\) interval that are plotted in Figure 11. Also shown in this figure are the loci of metal-poor giant branch and main-sequence stars listed in Tables 4 and 5 of Davidge & Harris (1995a). Only the AOB data were used to compute normal points, so the most evolved giant branch stages are absent in Figure 11.

The NGC 5272, NGC 6205, and NGC 6341 measurements fall close to the fiducial sequences in Figure 11; however, the NGC 6287 points, while having \((J - H)_{0}\) colors similar to those of the other clusters, have relatively red \((H - K)_{0}\) colors. Figure 7 of Davidge (1998) shows a similar tendency for NGC 6287 stars, although by an amount that is smaller than what is seen here. Figure 11 suggests either that the 2 \(\mu\)m SEDs of stars in NGC 6287 may differ from those in other clusters or that the reddening law toward NGC 6287 is peculiar. Near-infrared spectra would provide a direct means of investigating the SEDs of stars in NGC 6287 and provide further insight into the placement of NGC 6287 data points on the TCD.

4. ANALYSIS

The HB forms an almost vertical sequence in near-infrared CMDs, and so the infrared LF of HB stars provides a means of comparing HB content. The \(K\) HB LFs, normalized according to the total number of detected HB stars per cluster, are compared in Figure 12, where \(\Delta K\) refers to the difference in brightness between each point on the HB and the RGB tip. It is evident that these clusters define a range of HB contents: the NGC 6205 and NGC 6341 HBs are dominated by hot stars that are relatively faint in the infrared, whereas the HB stars in NGC 5272 and NGC 6287 are distributed over a broader range of near-infrared brightnesses, and hence temperatures. A Kolmogorov-Smirnov test indicates that the HB LFs of NGC 5272 and NGC 6205 differ at the 99% confidence level, whereas the HB LFs of NGC 6287 and NGC 6341 differ at the 98% confidence level. It is evident that significant information concerning HB content can be obtained from near-infrared observations, which has important implications for studies of heavily obscured metal-poor clusters.

If age is the dominant parameter defining HB content in these clusters, then NGC 6205 should be older than NGC 5272, whereas NGC 6341 should be older than NGC 6287.
Is there evidence to support this picture? VandenBerg & Durrell (1990) used the brightness difference between the MSTO and RGB tip to investigate the relative ages of clusters in a manner that does not require knowledge of cluster distance or reddening. A similar statistic, which we refer to as $\Delta_{\text{RGB}}$, which relies on the brightness of the SGB rather than the MSTO, can be constructed from the measurements in Table 3, and the results are listed in Table 4. The estimated uncertainties in $\Delta_{\text{RGB}}$ are $\pm 0.14$ mag, and the entries for NGC 5272, NGC 6287, and NGC 6341 agree within these limits. Although the $\Delta_{\text{RGB}}$ values for NGC 6205 are systematically larger than those of the other clusters, the significance of this result is not high; indeed, the $\Delta_{\text{RGB}}$ values for NGC 5272 and NGC 6205 in $J$ and $H$ differ at only slightly more than the 2 $\sigma$ level.

The $\pm 0.14$ mag uncertainties in $\Delta_{\text{RGB}}$ correspond to a $\pm 4$ Gyr age sensitivity. Hence, we will not consider these results further when assessing the relative ages of the clusters, and note that extremely high quality data will be required to obtain interesting age constraints from $\Delta_{\text{RGB}}$ measurements. Nevertheless, the general agreement between the $\Delta_{\text{RGB}}$ measurements for the various clusters lends confidence to the RGB tip and SGB brightnesses.

Another way to estimate relative cluster ages independent of reddening and distance is to register the CMDs using reference markers near the main sequence and then compare giant branch locations (see, e.g., VandenBerg, Bolte, & Stetson 1990; Sarajedini & Demarque 1990). For the current study the $(H, J-H)$ and $(K, J-K)$ CMDs for each cluster pair, defined using normal points computed by taking the mode of the color distribution within $\pm 0.25$ mag (RGB) and $\pm 0.1$ mag (SGB, MSTO) intervals along the brightness axes of Figures 7 and 9, were aligned along the horizontal and vertical axes using the MSTO colors and SGB brightnesses listed in Table 3, and the results are shown in Figures 13 and 14.

The lower giant branches of NGC 5272 and NGC 6205 overlap when the $(H, J-H)$ and $(K, J-K)$ CMDs are registered at the MSTO and SGB. Although there are differences below the MSTO, these are likely not significant as they occur near the faint limit of the data. The upper giant branches of NGC 5272 and NGC 6205, defined using the Cohen et al. (1978) data, are of greater interest, as they diverge on both CMDs. There is no hint of this behavior when only the AOB data are compared, and we suspect that the disagreement is spurious, arising from minor differences in the photometric calibration of the two NGC 5272 data sets. Indeed, if the Cohen et al. (1978) NGC 5272 measurements in Figure 14 are shifted by $\sim 0.04$ mag toward smaller $(J-K)$ values, then they give a better match to the AOB data for this cluster as well as to the NGC 6205 upper giant branch.

The lower giant branches of NGC 6287 and NGC 6341 also overlap when the $(H, J-H)$ CMDs of these clusters are registered at the MSTO and SGB. However, the cluster sequences show significant differences at the bright end, in that NGC 6287 has a steeper upper giant branch than NGC 6341; Davidge (1998) found that the upper giant branch of NGC 6287 is steeper than expected from theoretical models. Further differences between the CMDs of NGC 6287 and NGC 6341 are apparent in the right-hand panel of Figure 14, where the giant branch of NGC 6287 falls consistently to the left of the NGC 6341 sequence.

NGC 6287 is not the only inner spheroid cluster to show peculiar giant branch properties. Figure 4 of Minniti, Olczewski, & Rieke (1995) compares the $(K, J-K)$ giant branch loci of a number of inner spheroid clusters, and there is little or no evidence for correlations between mean metallicity, giant branch color, and/or slope. Moreover, the $(K, J-K)$ CMDs of the inner spheroid clusters M22 (Davidge & Harris 1995b) and M28 (Davidge, Côté, & Harris 1996) show peculiar giant branch morphologies when compared with outer halo clusters.

The error bars in the lower right-hand corner of each panel in Figures 13 and 14 show the range in relative RGB positions expected for $\pm 2$ Gyr age differences, as predicted from the $[\text{Fe/H}] = -2$ Berghbusch & VandenBerg (1992) isochrones, which we transformed onto the near-infrared observational plane using the procedure described by Davidge & Harris (1995a). The lower giant branches of NGC 5272 and NGC 6205 in Figures 13 suggest that the ages of these clusters differ by no more than $\pm 1$ Gyr. However, whereas the lower giant branches of NGC 6287 and NGC 6341 in Figure 13 are suggestive of a difference in age not exceeding $\pm 2$ Gyr, the comparison in the right-hand panel of Figure 14 is suggestive of an age difference approaching 4 Gyr, in the sense that NGC 6287 is older.

The LFs of globular clusters are sensitive to age variations at the brightness of the SGB (see, e.g., Berghbusch & VandenBerg 1992; Jimenez & Padoan 1996) and hence provide an independent means of checking relative ages deduced from CMDs. Although dynamical effects will alter the mass function, and thereby complicate cluster-to-cluster comparisons, the LF only becomes sensitive to these effects below the main sequence turnoff. The $J$, $H$, and $K$ LFs of each cluster pair, computed with 0.2 mag bins and excluding HB and AGB stars identified from the CMDs, are compared in Figures 15, 16, and 17.

**Fig. 10.** The $H-K$ color distributions for stars with $K$ between 12 and 14.5. $\Delta(H-K)$ is the difference between the observed $H-K$ and the peak value in each distribution. $P_{\text{norm}}$ is the number of stars per 0.02 mag $\Delta(H-K)$ interval divided by the total number of stars in the distribution. The standard deviation of each distribution, $\sigma_{\text{HB}}$, is also shown.
Fig. 11.—The $(J - H, H - K)$ two-color diagrams for NGC 5272, NGC 6205, NGC 6287, and NGC 6341. The points plotted in this figure are the modes of the color distribution in $\pm 0.25$ mag (RGB) or $\pm 0.1$ mag (SGB, MSTO) wide bins along the $K$ axis of the CMDs in Figs. 8 and 9; each point in this figure corresponds to the $J - H$ and $H - K$ normal points for a given $K$ interval. These normal points have been dereddened using the $E(B - V)$ values in Table 1 according to the Rieke & Lebofsky (1985) reddening law. Also shown are the loci defined by metal-poor dwarfs (solid line) and giants (dashed line), as listed in Tables 4 and 5 of Davidge & Harris (1995a). The open squares show the unreddened NGC 6287 normal points.

Fig. 12.—The $K$ HB LF s, based on stars identified from the $(K, J - K)$ CMDs. $n$ is the number of stars per 0.2 mag interval normalized according to the total number of HB stars in each field, which is the number shown in brackets under each cluster name. $\Delta K$ is the mag difference between each point on the HB and the RGB tip.
The LFs have been normalized along the vertical axis over a 3 mag interval on the upper giant branch, whereas the horizontal axis shows brightness measured with respect to the RGB tip. The $J$ LFs are not suitable for age comparisons, as incompleteness becomes significant on the SGB. However, the $H$ and $K$ LFs extend 0.5–1.0 mag fainter than the MSTO, and it is evident that the LFs of each cluster pair are not significantly different on the SGB. The effect of a $\pm 2$ Gyr age variation near the faint end of the SGB, derived from the Bergbusch & VandenBerg (1992) models, is shown in each figure, and the expected deviation is comparable to the uncertainties in each bin. Hence, the $H$ and $K$ LFs indicate that NGC 5272 and NGC 6205 are coeval, as are NGC 6287 and NGC 6341, to within $\pm 2$ Gyr.

5. SUMMARY AND DISCUSSION

$JHK$ images with angular resolutions approaching the diffraction limit of the 3.6 m CFHT have been obtained of the central regions of four metal-poor globular clusters: NGC 5272, NGC 6205, NGC 6287, and NGC 6341. The clusters were paired according to metallicity and distance to facilitate differential comparisons of cluster properties, and photometric measurements were made using the PSF-fitting routine in ALLSTAR. The crowded nature of the cluster fields necessitated the use of a single PSF for each cluster $+$ filter combination, and it is expected that PSF variations will introduce systematic errors of roughly 0.01 mag in the brightnesses of stars more than 8.5′ from the reference star, which account for roughly 80% of stars in the images. These errors may climb to a few hundredths of a mag for stars within 8.5′ of the reference star. Comparisons with published observations indicate that the photometric calibration is valid to within a few hundredths of a magnitude.

The HB contents of each cluster pair were investigated using the $K$ LF of HB stars. The “classical” second-parameter pair NGC 5272 and NGC 6205 provides an important test case to determine if differences between HB contents can be detected in the infrared, and the $K$ HB LFs of these clusters differ in a way that is consistent with what is seen at optical wavelengths. The temperature distribution of HB stars in NGC 6287 and NGC 6341 are also found to be significantly different.

Relative cluster ages have been determined using two
independent methods: (1) the color difference between the MSTO and the giant branch, measured from near-infrared CMDs, and (2) the near-infrared LFs of SGB stars. A third possible age indicator, the brightness difference between the RGB tip and a point on the SGB, was too insensitive to age to be of interest with the current data.

The near-infrared CMDs of NGC 5272 and NGC 6205, when registered near the MSTO and SGB, indicate that the ages of these clusters agree to within $\pm 1$ Gyr, while the SGB LFs are suggestive of ages that agree to within $\pm 2$ Gyr. These data thus do not support the notion that age is the second parameter (see, e.g., Salaris & Weiss 1997; Stetson, VandenBerg, & Bolte 1996; but see also Chaboyer et al. 1996 and Lee, Demarque, & Zinn 1994). F. Grundahl (1998, private communication) has obtained high-precision ground-based observations of NGC 5272 and NGC 6205 in the Stromgren filter system, and his data are also consistent with little or no difference in age.

The problems arising from field star contamination and differential reddening that frustrate efforts to study the outer regions of NGC 6287 (see, e.g., Davidge 1998; Stetson & West 1994) are largely avoided when the high-density central area of the cluster is studied, and the current data provide insight into the relative ages of NGC 6287 and NGC 6341. The $(H, J-H)$ CMDs and near-infrared LFs suggest that the ages of these clusters agree to within $\pm 2$ Gyr, and thus do not support the hypothesis that the inner regions of the Galaxy formed significantly before the outer halo, contrary to what might be inferred from the properties of RR Lyrae variables in Baade's window (Lee 1992a). On the other hand, the $(K, J-K)$ CMDs of NGC 6287 and NGC 6341 ostensibly suggest that the former is 4 Gyr older than the latter. A similar difference in age was found when the $(K, J-K)$ CMD of the [Fe/H] $= -1.4$ globular cluster M28 ($R_{GC} \sim 2.5$ kpc) was compared with CMDs of clusters having $R_{GC} \geq 3$ kpc (Davidge et al. 1996; Davidge & Harris 1997). NGC 6287 is thus the second inner spheroid cluster to have an extremely old age inferred from the $(K, J-K)$ CMD. However, the significance of this last result is not clear, as the location of NGC 6287 stars on the near-infrared TCD suggest that the 2 $\mu$m photometric properties of metal-poor stars in this cluster differ from those of outer halo objects. This brings into question the validity of $(K, J-K)$ CMD comparisons between inner and outer halo clusters.

The relative ages of NGC 6287 and NGC 6341 notwithstanding, NGC 6287 appears to be a unique object. With a plunging orbit (van den Bergh 1993), and a broadly populated HB (§ 4), NGC 6287 has the characteristics of van den Bergh's (1993) $\alpha$-population of globular clusters, the other members of which have $R_{GC} \gtrsim 8$ kpc. The discovery of HB stars spanning a range of temperatures in NGC 6287 also
challenges Lee's (1992b) finding that the HB content of inner spheroid globular clusters can be characterized by a single parameter—metallicity; Rich et al. (1997) reach a similar conclusion for metal-rich globular clusters. Deep photometric surveys of other metal-poor clusters in the inner Galaxy will reveal whether the HB properties of NGC 6287 are truly unique or representative of a still largely unstudied population of inner spheroid clusters.

If NGC 6287 is a bona fide member of the inner spheroid, then it is a remnant of what was once a much more populous cluster system, the members of which, especially those that had low masses, low concentrations, and circular orbits, were disrupted by dynamical interactions (see, e.g., Murali & Weinberg 1997; Vesperini 1997, and references therein). If this is the case, then the initial properties of NGC 6287 were undoubtedly very different from what are observed now. For example, selective pruning of low-mass stars has likely occurred, and the current mass may be more than 30% lower than the initial value (Murali & Weinberg 1997). Studies of the main-sequence mass function, especially near the center of NGC 6287, where the signatures of mass segregation are conspicuous (see, e.g., Weinberg 1994; Pryor, Smith, & McClure 1986), will provide clues into the dynamical history of this cluster.

The discovery of the Sagittarius dwarf spheroidal (Ibata, Gilmore, & Irwin 1994), which has an entourage of four globular clusters (Ibata et al. 1994; Da Costa & Armandroff 1995), suggests that accretion events may play a significant role in the evolution of galaxies, and that the present-day sample of globular clusters in the inner Galaxy may contain interlopers that formed in external systems. In fact, the radius and metallicity of NGC 6287 are not inconsistent with a dwarf spheroidal origin. Indeed, van den Bergh (1994) finds that the globular clusters in the Fornax dwarf spheroidal have radii comparable to those of globular clusters in the inner halo, so the compact size of NGC 6287 is not an unambiguous indicator of an inner spheroid origin. Moreover, the metallicities of globular clusters in the dwarf satellite companions of the Galaxy (Da Costa & Armandroff 1995) and M31 (Da Costa & Mould 1988) are typically (but, as demonstrated by Terzan 7, not exclusively) very
metal poor, like NGC 6287. Therefore, while the observational characteristics of NGC 6287 are ostensibly consistent with this cluster being formed in situ as part of the inner spheroid (van den Bergh 1993), the evidence is not ironclad.

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