The Metallicity of the Red Giant Branch in the Disk of NGC 6822

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ABSTRACT. Deep J, H, and K' images obtained with the Canada-France-Hawaii Telescope adaptive optics system are used to investigate the metallicity of red giant branch (RGB) stars in three fields in the disk of the Local Group dwarf irregular galaxy NGC 6822. The slope of the RGB on the (K, J−K) color-magnitude diagrams indicates that [Fe/H] = −1.0 ± 0.3. The locus of the RGB is bluer than that of globular clusters with the same RGB slope by an amount that is consistent with the majority of RGB stars in these fields having an age near 3 Gyr. It is demonstrated that if RGB stars in NGC 6822 are this young, then the metallicity computed from the RGB slope may be ~0.05 dex too low. Finally, the metallicity computed from the RGB slope is lower than spectroscopic-based metallicities for young stars in NGC 6822, and it is concluded that Δ[Fe/H]/Δt = −0.2 ± 0.1 dex Gyr⁻¹ in NGC 6822 during the past few gigayears.

1. INTRODUCTION

NGC 6822 is an isolated dwarf irregular (dIrr) galaxy belonging to the Local Group cloud (Mateo 1998). As the nearest isolated dIrr galaxy, NGC 6822 is an important laboratory for probing the evolution of this type of system. It is therefore not surprising that the stellar content of NGC 6822 has been the subject of a number of investigations, and these have found stars spanning a broad range of ages.

The youngest stars in NGC 6822 are distributed in an irregular fashion in and around the central bar (Hodge 1980; Hodge et al. 1991; Marconi et al. 1995; Gallert et al. 1996b; Wyder 2001). Gallert et al. (1996a) conclude that the star formation rate (SFR) in NGC 6822 has been constant over much of the age of the galaxy, with the exception of a drop in activity during intermediate epochs. However, the SFR has increased during the past 1 Gyr (Marconi et al. 1995; Gallert et al. 1996b; Wyder 2001), and there are morphological signatures that are suggestive of a tidal interaction (Hutchings, Cavanagh, & Bianchi 1999; de Blok & Walter 2000), which may have triggered the recent increase in star-forming activity. NGC 6822 is also surrounded by an extended stellar halo that has been traced with carbon stars (Letarte et al. 2002), suggesting that during intermediate epochs star formation was distributed over a larger area than is currently the case.

Tolstoy et al. (2001) conclude that [Fe/H] in NGC 6822 grew steadily with time from early epochs until 3 Gyr in the past, at which point the pace of chemical enrichment accelerated as a result of an increase in the SFR. For comparison, Wyder (2001) suggests that NGC 6822 may have experienced a rapid initial chemical enrichment and that [Fe/H] has been constant or only slowly changing with time during the past 7 Gyr with [Fe/H] = −1.0. However, Wyder (2001) also emphasizes that the age-metallicity degeneracy that plagues photometric studies of old populations renders his chemical enrichment history of NGC 6822 very uncertain more than 3 Gyr in the past.

There is a growing body of spectroscopic observations of sources in NGC 6822 that can be used to investigate directly the chemical enrichment history of the galaxy. Pagel, Edmunds, & Smith (1980) and Skillman, Terlevich, & Melnick (1989) investigated the spectra of H ii regions in NGC 6822 and found [O/H] that is intermediate between the SMC and LMC. The abundances obtained from H ii regions are consistent with those measured from the absorption-line spectra of bright supergiants (Muschielok et al. 1999; Venn et al. 2001). Chandar, Bianchi, & Ford (2000) discussed spectroscopic observations of H ii regions outside of the central regions of NGC 6822 and found [O/H] that is significantly different from that measured by Pagel et al. (1980) and Skillman et al. (1989), suggesting that [O/H] may vary across the galaxy. Venn et al. (2001) noted that an abundance gradient is consistent with the highest quality abundance measurements in NGC 6822 but also stressed that additional data are needed to characterize with confidence the radial chemical properties of the galaxy. Chandar et al. (2000) also investigated intermediate-age clusters in NGC 6822 and found metallicities that are 0.5–1.0 dex lower than in clusters with comparable ages in the LMC and SMC. Tolstoy et al. (2001) measured the strength of the near-infrared Ca ii lines in a sample of RGB stars and found [Fe/H] ranging from −2 to −3.0, with a peak near [Fe/H] = −0.9. The metallicity distribution function (MDF) constructed by Tolstoy et al. (2001)
The Schlegel, Finkbeiner, & Davis (1998) dust maps give a significant extinction and contamination from foreground stars. Attempts to estimate metallicities from the color of the RGB are sensitive to the age-metallicity degeneracy that complicates efforts to understand the chemical enrichment history of this region of the galaxy during old and intermediate epochs. The metallicity is estimated from the slope of the RGB on the $(K, J-K)$ color-magnitude diagram (CMD). The slope of the RGB in infrared CMDs is insensitive to uncertainties in the reddening and the photometric calibration (CMD). The slope of the RGB on the $(K, J-K)$ CMD in § 4. A detailed description of the AOB, which uses natural guide stars to monitor wave-front distortions, has been given by Rigaut et al. (1998). KIR is the dedicated infrared imager for the AOB and contains a pixel Hg:Cd:Te array, 1024 by 1024 pixels, and has been calibrated as a metallicity indicator using CMDs of globular clusters spanning a range of metallicities (e.g., Ferraro et al. 2000, hereafter F2000). The RGB slope is also insensitive to the age-metallicity degeneracy that complicates efforts to estimate metallicities from the color of the RGB.

NGC 6822 is viewed at a low Galactic latitude, so there is significant extinction and contamination from foreground stars. The Schlegel, Finkbeiner, & Davis (1998) dust maps give a foreground reddening of $E(B-V) = 0.24$ near the center of NGC 6822, and this is adopted as the baseline for the present study, although there is significant internal extinction near star-forming regions in NGC 6822 (§ 5). A distance modulus of 23.49, which was computed from Cepheids and is consistent with the brightness of the RGB tip (Gallart, Aparicio, & Vilchez 1996c), is also adopted here.

The paper is structured as follows. The observations and reductions are described in § 2, while the CMDs, luminosity functions (LFs), and two-color diagrams (TCDs) of the fields are discussed in § 3. The metallicity of the RGB is estimated from the slope of the RGB on the $(K, J-K)$ CMD in § 4. A summary and discussion of the results follow in § 5.

## 2. OBSERVATIONS AND REDUCTIONS

The data were recorded during the nights of 2000 September 9/10 and 10/11 (UT) with the Canada-France-Hawaii Telescope (CFHT) Adapative Optics Bonnette (AOB) and KIR camera. A detailed description of the AOB, which uses natural guide stars to monitor wave-front distortions, has been given by Rigaut et al. (1998). KIR is the dedicated infrared imager for the AOB and contains a 1024 × 1024 pixel Hg:Cd:Te array, with each pixel subtending 0′′034 on a side.

Three fields in the disk (i.e., outside of the bar) of NGC 6822 were imaged through $J, H,$ and $K'$ filters. Each field contains a moderately bright ($R \leq 15$) AO guide star, and the names and coordinates of these stars are listed in Table 1. The field locations are marked in Figure 1, which shows a portion of the Digitized Sky Survey centered on NGC 6822.

Each AO guide star was positioned near the center of the KIR science field to reduce the effects of anisoplanicity near the edges of the detector. Five 60 s exposures were recorded in each filter at the corners of a $0′′.5 \times 0′′.5$ dither pattern, and the total exposure time per filter is thus 60 s × five exposures × four dither positions = 1200 s. The sky was photometric when these data were recorded, and the seeing was very good. Stars in the corrected images have FWHM = 0′′10–0′′15, and the angular resolution of the $K'$ images is the telescope diffraction limit.

The processing sequence consisted of the following steps: (1) dark subtraction; (2) division by a dome flat, which was constructed by differencing images of a dome spot taken with the dome lights on and off to remove thermal artifacts; (3) the subtraction of a calibration image to remove interference.
fringes and the thermal signatures of warm objects along the light path, which was constructed by combining images of different fields to suppress sky sources; and (4) the subtraction of the DC sky level, which was measured separately for each exposure. The results were aligned on a field-by-field basis to correct for the dither offsets and then median-combined to reject cosmic rays and bad pixels. The combined images were trimmed to the region having a full 20 minute exposure time, and the final \( K' \) images are shown in Figures 2, 3, and 4. The AO guide star is the bright central source in each figure, and the first diffraction ring can be seen around moderately bright stars in each of the fields.

3. RESULTS

3.1. Photometric Measurements

Stellar brightnesses were measured with the point-spread function (PSF) fitting routine ALLSTAR (Stetson & Harris 1988), which is part of the DAOPHOT (Stetson 1987) photometry package. A single PSF was constructed for each field+filter combination. While anisoplanicity causes the PSF to change with angular distance from the AO guide star, observations of globular clusters with the CFHT AOB indicate that, at least for moderate levels of AO compensation during typical Mauna Kea seeing conditions, the PSF typically changes on a characteristic angular scale that exceeds the KIR field (e.g., Davidge & Courteau 1999; Davidge 2001). The relatively large isoplanatic patch is a consequence of the superb seeing conditions on Mauna Kea, and the PSF will change over smaller angular scales at sites with poorer atmospheric conditions.

There are three pieces of evidence that justify the use of a single PSF. First, a classical signature of anisoplanicity is the radial elongation of stellar images near the field edges (McClure et al. 1991), with the major axis pointing toward the guide star.
and this distortion is not seen in these data. Second, tight, well-defined CMDs are produced from these data when a uniform PSF is assumed (§ 3.2), demonstrating that anisoplanicity causes only moderate scatter in the photometric measurements. Third, the encircled energy curves of PSFs constructed from stars in two different radial intervals from the AO guide star in the $K^\prime$ field 1 data, which are shown in Figure 5, demonstrate the radial stability of the PSF. The radial intervals used to construct the encircled energy curves sample comparable areas in the KIR science field, and the PSFs were constructed from similar numbers of stars. The two curves in Figure 5 agree to within a few percent inside the PSF-fitting radius.

The photometric calibration is based on observations of UKIRT faint standard stars (Hawarden et al. 2001) that were recorded throughout the two-night observing run. The wings of AO-corrected PSFs extend out to distances in excess of an arcsecond, so the brightnesses of the standard stars were measured in 2° radius apertures to sample as much light as possible; measurements with larger apertures were found not to contain additional signal. The uncertainty in the photometric zero points, computed from the residuals about the mean, is $\pm 0.04$ mag in $K$. For consistency with the standard-star observations, 2° radius aperture measurements of the PSF stars were used to calibrate the NGC 6822 observations. These aperture measurements were made after all stars but those used to construct the PSF were subtracted from the images. The use of large-aperture aperture measurements to calibrate the data greatly reduces the sensitivity to field-to-field variations in the Strehl ratio (e.g., Davidge 2002).

3.2. ($K, H-K$) and ($K, J-K$) CMDs

When compared with $J-H$ or $J-K$, the $H-K$ color changes slowly with effective temperature for all but the coolest stars, and so the width of the RGB in the ($K, H-K$) CMD is used here as a means of constraining the uncertainties in the photometric measurements due to anisoplanicity. The ($K, H-K$) CMDs of the NGC 6822 fields are shown in Figure 6, and the RGB is clearly evident as a vertical sequence near $H-K = 0.2$. The scatter envelope predicted from the artificial-star experiments is slightly smaller than the observed width of the RGB. In particular, the standard deviation in the $H-K$ colors of stars with $K$ between 18 and 19 in each field is typically $\pm 0.06$ mag, while the dispersion predicted from the artificial-star experiments in this same magnitude interval is $\pm 0.04$ mag. The residual scatter due to the intrinsic properties of stars in NGC 6822, differential reddening, and anisoplanaticism, which can be computed by subtracting the predicted scatter from the measured scatter in quadrature, is then $\pm 0.04$ mag. This indicates that anisoplanicity does not introduce scatter in the $H-K$ colors at a level in excess of a few hundredths of a magnitude, and this is of the same order as the uncertainties predicted from the encircled energy curves that are compared in Figure 5.

The ($K, J-K$) CMDs of the three fields are compared in Figure 7. The RGB is the dominant feature in each CMD, indicating that these fields are dominated by old or intermediate-age populations. While the upper RGBs of fields 1 and 2 are not well defined, the RGB of field 3 bends near the bright end, indicating that RGB stars in this region of NGC 6822 are not extremely metal poor. The onset of the RGB in all three fields occurs near $K = 17$. Finally, given the low Galactic latitude of NGC 6822, it is likely that some of the stars on the ($K, J-K$) CMDs that do not fall along the RGB belong to the foreground, especially those that are redder than the RGB.
Some of the objects in fields 1 and 3 with $J-K \sim 0$ may be bright main-sequence stars in NGC 6822.

The photometric errors are largest, and hence most likely to dominate over intrinsic star-to-star differences in photometric properties, at the faint end, and there is good agreement between the predicted and observed scatter in the $(K, J-K)$ CMDs when $K \geq 19$. However, at the bright end the RGB on the $(K, J-K)$ CMD is noticeably wider than expected from photometric errors alone. A number of factors could introduce scatter in the CMD, including (1) the AGB, (2) differential reddening, (3) a range in metallicity, and (4) an age dispersion. Limits on age and metallicity dispersions in the disk of NGC 6822 are calculated in § 4.

3.3. $K$ LFs and $(J-H, H-K)$ TCDs

The $K$ LFs of stars that are detected in both $H$ and $K'$ and have $H-K$ colors within $\pm 0.2$ mag of the RGB ridgeline on the $(K, H-K)$ CMD are shown in Figure 8. A composite LF was also created by summing the LFs of the individual fields to reduce the small number statistics that dominate the LFs of the individual fields near the RGB tip, and the result is shown in the bottom panel of Figure 8. The LFs follow power laws at the faint end, and the method of least squares was used to fit a power law to the entries with $K$ between 18 and 20 in the summed LF; this brightness interval was selected to fit the power law since it is fainter than the RGB tip, and incompleteness is not an issue. The fitted power law has an exponent $0.23 \pm 0.06$, which agrees with the exponents measured in Galactic globular clusters by Davidge (2000, 2001).

The $(J-H, H-K)$ TCD can be used to identify objects with nonstellar near-infrared spectral energy distributions (SEDs), such as emission-line galaxies, as well as stars with extreme SEDs, such as long-period variables (LPVs). The TCDs of the three fields, corrected for foreground extinction, are shown in
Figure 7.—\((K, J-K)\) CMDs of fields 1, 2, and 3. The RGB is clearly seen in each CMD, and the RGB in all three fields terminates near \(K = 17\). The dashed lines show the scatter envelope predicted from the artificial-star experiments. While there is good agreement between the observed and predicted scatter at the faint end, when \(K \leq 19\) the observed scatter exceeds that predicted from photometric errors alone.

Figure 9. The majority of objects fall along the globular cluster giant branch sequence, which is not unexpected given that the RGB is the dominant feature in the NGC 6822 CMDs. There are also a modest number of stars that appear to be LPVs, as well as some sources with nonstellar SEDs.

4. THE RGB SLOPE AND METALLICITY

Small number statistics complicate efforts to track the upper portions of the RGB on CMDs, and this affects efforts to measure the slope of the RGB. Therefore, the data from all three fields were combined to better define the upper portions of the RGB. This was done by calculating normal points for each field and then computing a mean normal point sequence for all three fields. Normal points were calculated by finding the mean \(J-K\) color in ±0.25 mag bins along the \(K\) axis of each \((K, J-K)\) CMD, with an iterative 2.5 \(\sigma\) rejection scheme to suppress outliers. A single bulk shift along the \(J-K\) axis was then applied to all of the data points in each field such that the normal point sequence for that field best matched the mean normal point sequence. The field-to-field scatter among the normal point sequences is ±0.05 mag, which is comparable to the uncertainty in the \(J-K\) calibration based on the standard-star measurements.

The composite \([M_K, (J-K)_0]\) CMD, assuming the reddening and distance modulus discussed in § 1, is shown in the left panel of Figure 10. The data from the various fields are well mixed with no systematic differences near the RGB tip, which is consistent with the three fields having similar RGB mor-
Fig. 8.—$K$ LFs of fields 1, 2, and 3, and their sum; $N_{ij}$ is the number of stars per 0.2 mag interval in $K$. The dashed line in the bottom panel shows a power law that was fitted to the summed LF between $K = 18$ and 20; the power law has an exponent $0.23 \pm 0.06$. The dotted line shows this same power law, but shifted to represent a population that is only 20% the size of that on the observed LF to simulate the contribution expected from a pure AGB component. Note that the observed LF consistently falls above the AGB sequence when $K < 16.8$, suggesting that this magnitude range is dominated by RGB stars.

Phalanges. The upper RGB is better defined than was the case from the CMDs of the individual fields, and $M_{K}^\text{RGB} \sim -6.5$.

To suppress the effects of non-RGB stars and photometric scatter on the slope measurement, a final set of normal points was computed from the composite CMD, and the sequence defined by these normal points is shown in the middle panel of Figure 10. The slope measured from a least-squares fit to the normal points is $\Delta(J-K)/\Delta K = -0.108 \pm 0.007$. This slope measurement serves as the basis for computing [Fe/H] in the disk of NGC 6822.

F2000 give a relation between RGB slope and metallicity in their Figure 12 that was determined from the CMDs of globular clusters spanning a range of metallicities; however, F2000 measured RGB slopes using individual CMD data points, rather than normal points. This is an important consideration, as the use of normal points computed at uniform magnitude intervals effectively assigns each portion of the RGB equal weight when measuring the RGB slope, whereas less weight is assigned to the uppermost portion of the RGB when individual CMD points are used, since the number of stars per unit brightness interval decreases toward the RGB tip.

Table 2 of F2000 lists the colors of various globular cluster RGBs at several $M_{K}$, and these were used to calibrate the metallicity dependence of RGB slopes measured from normal points. The slopes of the clusters in the F2000 sample were measured from the entries in their Table 2, supplemented with $M_{K}^\text{RGB}$ from their Table 6 and RGB-tip colors from the CMDs plotted in their Figure 1. NGC 6528 and NGC 6553 were not considered, as there is significant scatter on the upper RGBs of these clusters in Figure 1 of F2000. A linear least-squares
Fig. 9.—(J−H, H−K) TCDs of fields 1, 2, and 3. The data for each field have been corrected for foreground reddening, and the error bars show the uncertainty in the photometric calibration. A reddening vector with a length corresponding to $A_V = 0.5$ mag is also shown, and it is evident that extinction causes stars to move along an almost vertical track on this diagram. The solid line is the sequence for metal-poor globular cluster giants from Fig. 12 of Davidge (2000), while the dotted line is the sequence defined for LMC LPVs from Fig. 9 of Davidge (1998).

fit to these slope measurements gives

$$[\text{Fe/H}] = (-16.95 \pm 2.28) \frac{\Delta J-K}{\Delta K} - (2.87 \pm 0.07). \quad (1)$$

This normal point-based calibration differs from that determined from measurements of individual stars. For example, whereas a system with $[\text{Fe/H}] = -0.7$ is predicted to have $\Delta J-K/\Delta K = -0.097$ from the relation in Figure 12a of F2000, equation (1) predicts that $\Delta J-K/\Delta K = -0.128$ for this same system.

Equation (1) indicates that $[\text{Fe/H}] = -1.0 \pm 0.3$ for the disk of NGC 6822, where the quoted error includes the uncertainties in the coefficients in equation (1) and the uncertainty in the slope measurement. This metallicity can be checked using the RGB-tip brightness in $K$ and the color of the RGB, both of which are sensitive to metallicity.

The brightness of the RGB tip, $M_k^{\text{RGB}}$, becomes brighter as $[\text{Fe/H}]$ increases. Models by Girardi et al. (2000, hereafter G2000) predict that $M_k^{\text{RGB}} = -5.6$ in an old population with $[\text{Fe/H}] = -1.6$ and $M_k^{\text{RGB}} = -6.3$ when $[\text{Fe/H}] = -0.6$. The empirical calibration of F2000 gives slightly brighter RGB-tip values, with $M_k^{\text{RGB}} = -6.0$ and $M_k^{\text{RGB}} = -6.6$ for globular clusters with $[\text{Fe/H}] = -1.6$ and $-0.7$. The G2000 models also predict that at a fixed metallicity $M_k^{\text{RGB}}$ becomes fainter as age decreases, although the differences in $M_k^{\text{RGB}}$ due to age are relatively modest compared with those due to metallicity; for example, between $t = 16$ and 3 Gyr, the $z = 0.001$ (i.e.,
Fig. 10.—Left panel: Composite \([M_K, (J-K)_0]\) CMD of fields 1, 2, and 3. The data from fields 1, 2, and 3 are plotted as crosses, triangles, and squares, respectively. A foreground reddening of \(E(B-V) = 0.24\) (Schlegel et al. 1998) and a distance modulus of 23.49 (Gallart et al. 1996c) have been assumed. Middle panel: Normal point sequence (solid line) calculated from the data in the left panel. Also shown in this panel are the RGB sequences for 47 Tuc (dashed line), NGC 6121 (dotted line), and NGC 7078 (dash-dotted line) from F2000. Note that the NGC 6822 RGB falls blueward of the 47 Tuc and NGC 6121 sequences, even though the metallicity measured from the RGB slope falls between the two clusters. Right panel: \(z = 0.001\) isochrones extending up to the RGB tip for \(\log (t_G) = 9.3, 9.6, 9.9, \) and \(10.2\) from G2000. These models indicate that the difference in color between the RGB ridgeline in NGC 6822 and globular clusters having the same metallicity could occur if the majority of RGB stars in NGC 6822 have an age near 3 Gyr.

\([\text{Fe/H}] = -1.2\) G2000 models predict that \(M_K^{\text{GBT}}\) dims by only 0.2 mag. The F2000 calibration predicts that \(M_K^{\text{GBT}} = -6.4 \pm 0.2\) for an old system with \([\text{Fe/H}] = -1.0 \pm 0.3\), which agrees with the RGB-tip brightness measured for the disk of NGC 6822.

While the \(K\) brightness of the RGB tip in the disk of NGC 6822 is consistent with the measured metallicity, the RGB ridgeline is bluer than expected for an old, \([\text{Fe/H}] = -1\) population. This is demonstrated in the middle panel of Figure 10, where the RGB sequences of 47 Tuc (\([\text{Fe/H}] = -0.7\)), NGC 6121 (\([\text{Fe/H}] = -1.2\)), and NGC 7078 (\([\text{Fe/H}] = -2.1\)) from F2000 are compared with the NGC 6822 normal point sequence. The NGC 6822 giant branch falls blueward of both the 47 Tuc and NGC 6121 sequences, even though the metallicity estimated from the RGB slope falls midway between the metallicities of these clusters. This color offset may indicate that RGB stars in NGC 6822 and globular clusters have different ages, in the sense that stars in NGC 6822 are younger.

The age sensitivity of RGB sequences is investigated in the right panel of Figure 10, which shows \(z = 0.001\) isochrones of G2000 for populations with \(\log (t_G) = 9.3, 9.6, 9.9, \) and \(10.2\). The NGC 6822 sequence in Figure 10 falls \(\sim 0.1\) mag blueward of the expected location for an old stellar system having the same metallicity, and this is consistent with the RGB
stars in NGC 6822 having a typical age of ~3 Gyr if globular clusters have ages ≥10 Gyr. Such a relatively young age for RGB stars in NGC 6822 is consistent with a star-forming history that is not weighted toward early epochs, but in which there has been significant recent star formation.

An age difference between NGC 6822 and globular clusters will have only a modest impact on the metallicity estimated from the RGB slope, and the G2000 isochrones in the right panel of Figure 10 can be used to quantify any age-related systematic effects. To simulate the process used to create the NGC 6822 normal points, the isochrones were sampled at 0.5 mag increments in $M_V$, and the slopes measured from the results when $M_V ≤ -5.5$ are summarized in Table 2, along with the [Fe/H] computed from equation (1). The isochrones are steeper than the giant branches of actual clusters having the same metallicity, and this has been noted in other model sequences (e.g., Davidge 2000). The absolute calibration of the metallicity scale notwithstanding, the metallicities computed from the log ($t_e$) = 9.3 and 10.2 sequences differ by only 0.16 dex, whereas the metallicities computed from the log ($t_e$) = 9.6 and 10.2 isochrones differ by only 0.05 dex. Therefore, if RGB stars in NGC 6822 have a typical age of 3 Gyr, then the metallicity from the RGB slope may be underestimated by ~0.05 dex, which is smaller than the random uncertainties in the metallicity estimate.

The disk of NGC 6822 likely contains stars spanning a range of ages and metallicities, and constraints on possible age and metallicity dispersions can be estimated from the scatter in the composite CMD on the upper portion of the RGB. The RGB at $M_V = −5.5$ is well populated, so the width of the CMD near this point is used to set constraints on any age and/or metallicity spread in the disk of NGC 6822. The standard deviation in ($J−K_s$) of stars with $M_V$ between −5.4 and −5.6 is ±0.07 mag. The artificial-star experiments indicate that photometric errors contribute a ±0.03 mag scatter in $J−K$ at this brightness. After subtracting this contribution in quadrature from the observed color dispersion, there then remains ±0.06 mag scatter in ($J−K_s$), that is not due to photometric errors. Comparisons with the F2000 globular cluster sequences indicate that this range in color could result from a ±0.2 dex metallicity spread, while the G2000 isochrones indicate that a ±0.5 dex spread in log ($t_e$) could also explain the observed scatter. The actual spreads in age and metallicity in the disk of NGC 6822 will of course be smaller than these values, as there is likely a dispersion in both age and metallicity. In addition, differential reddening and anisoplanicity may also contribute to the width of the RGB.

5. DISCUSSION AND SUMMARY

The slope of the RGB on the ($K_s$, $J−K_s$) CMD indicates that RGB stars in the disk of the Local Group dIrr galaxy NGC 6822 have a typical metallicity [Fe/H] = −1.0 ± 0.3. This agrees with the mean metallicity measured for giants by Tolstoy et al. (2001) from the strength of the near-infrared Ca $\Pi$ absorption lines. The agreement between the metallicities determined from the RGB slope and the Ca $\Pi$ lines is noteworthy, as they are based on independent data sets that have different sensitivities to factors such as reddening and chemical mixture.

Internal reddening is significant in some parts of NGC 6822. Multicolor observations of massive stars indicate that $E(B−V)$ varies between 0.25 and 0.45 (Bianchi et al. 2001); for comparison, Wilson (1992) finds that $E(B−V) = 0.45$, which is much higher than the foreground value, based on the ridgeline of upper main-sequence stars. Internal reddening is highest near star-forming regions, and studies of the colors of young stars with known spectral types suggest that there is a systematic reddening gradient in NGC 6822, such that $E(B−V)$ = 0.45 near the middle of the galaxy, which is the most active star-forming region, and $E(B−V)$ = 0.26 at the periphery (Massey et al. 1995). This is qualitatively consistent with what was measured by Wyder (2001), who found that $E(B−V) = 0.34$ near the bar and $E(B−V) = 0.23$ in the disk. These studies thus indicate that foreground dust is the dominant source of reddening in the disk of NGC 6822.

The RGB slope determined from the ($K_s$, $J−K_s$) CMD is a relative measurement made from a self-contained data set and hence is not sensitive to the mean line-of-sight reddening, although differential reddening will smear the RGB and complicate efforts to define the RGB ridgeline. The metallicity estimated from Ca $\Pi$ line strengths is moderately sensitive to the line-of-sight reddening. The relative $V$ brightness of RGB stars with respect to the horizontal branch (HB) is used to correct for surface gravity effects in Ca $\Pi$ line strengths (e.g., Armandroff & Da Costa 1991) and, lacking deep photometry, Tolstoy et al. (2001) adopted a single HB brightness with only the foreground reddening value. The Tolstoy et al. (2001) field includes the bar, so some of the stars may be subject to reddening that exceeds the foreground value. By adopting a fixed HB brightness, Tolstoy et al. (2001) underestimated the metallicities of these stars. For RGB stars outside of active star-forming regions, this effect will not be large; however, for stars with $E(B−V) = 0.45$, which appears to be the upper limit of line-of-sight reddening in NGC 6822, the metallicity computed

| $t_e$ (Gyr) | $Δ(J−K)_{V}ΔK$ | [Fe/H]a |
|------------|----------------|--------|
| 9.3        | −0.074 ± 0.002 | −1.62  |
| 9.6        | −0.080 ± 0.004 | −1.51  |
| 9.9        | −0.083 ± 0.004 | −1.46  |
| 10.2       | −0.083 ± 0.004 | −1.46  |

a Computed from eq. (1).
by Tolstoy et al. (2001) is 0.16 dex too low. The main consequence is that the mean metallicity found by Tolstoy et al. (2001) is a lower limit, while the metallicity dispersion determined from their data (±0.5 dex, compared with ±0.2 dex from the width of the RGB in § 4) is an upper limit.

The use of the Ca II lines to measure [Fe/H] assumes that the [Ca/Fe] ratio matches that of the globular clusters that are used to define the metallicity calibration. This assumption may not hold, as the chemical enrichment history of galaxies that have experienced star formation, and hence chemical enrichment, over a large fraction of the age of the universe will likely have been systematically different from that of globular clusters. For comparison, the overall photometric properties of the RGB, including the slope, are affected by the total metal content, rather than that of a single species.

When applied to systems more distant than the Milky Way and its immediate companions, metallicities based on the RGB slope and Ca II line strengths rely on observations of stars that are relatively faint and hence may be susceptible to large photometric errors and systematic effects introduced by crowding. For example, the RGB must be traced down to the HB to measure the RGB slope. However, the fields studied here are in the low-density outer regions of NGC 6822 and are not susceptible to crowding. In fact, each of the fields contains 200–300 stars on the upper 4 mag in K of the RGB, so the stellar density is ∼0.2 stars arcsec⁻², or only 0.004 stars per angular resolution element, as defined by the FWHM of the PSF.

The metallicity calibration used in the current paper assumes that RGB stars in NGC 6822 have ages comparable to those of globular clusters. In § 4 it is argued, on the basis of the color of the RGB, that the majority of RGB stars in the NGC 6822 disk have an age of roughly 3 Gyr. While the model isochrones shown in the right panel of Figure 10 indicate that the slope of the RGB on the (K, J−K) CMD is not sensitive to age at a fixed metallicity, if subsequent photometric measurements verify the relatively young ages of RGB stars in NGC 6822 then the metallicity derived from equation (1) will be ∼0.05 dex too low.

The giant branch in the composite NGC 6822 CMD of fields 1, 2, and 3 is actually a mix of AGB and RGB stars, and the presence of AGB stars may affect the slope measurement and the color of the RGB locus. A distinct AGB sequence is not seen in the CMDs because photometric errors blend the AGB and RGB. Nevertheless, the AGB has bluer colors than the RGB, with the color difference between the AGB and RGB decreasing toward the RGB tip. Therefore, AGB stars may systematically bias the slope measurement and shift the RGB locus to bluer colors. While we have not attempted the difficult task of quantifying the effects of AGB contamination on the color and slope of the RGB, it should be noted that the number of AGB stars in a given brightness interval is much lower than that of RGB stars (n_{AGB}/n_{RGB} ∼ 0.25), and the iterative rejection technique used to compute the normal points will reject objects with obvious outlying colors.

AGB stars could also cause the brightness of the RGB tip to be overestimated. This issue can be investigated by comparing the observed number of stars in a given brightness interval with those expected from a combined RGB+AGB population, which occurs below the RGB tip, and a pure AGB population, which occurs above the RGB tip. The dotted line in the lower panel of Figure 8 shows the expected number counts from a pure AGB population. This sequence was created by shifting the power law derived in § 3.3 from faint RGB stars along the vertical axis to represent a population that has 20% of the total number of faint RGB+AGB stars. When K > 16.8 (M_K > −6.8), each entry in the composite LF consistently falls above the AGB trend, as expected if stars that are a mix of AGB and RGB stars. This comparison supports the adopted RGB-tip brightness of M_K = −6.5 that was measured in § 4.

We close by noting that Muschielok et al. (1999) and Venn et al. (2001) conclude that [Fe/H] = −0.5 ± 0.2 in bright NGC 6822 supergiants. These stars are considerably younger than RGB stars, for which [Fe/H] = −1.0 ± 0.3 based on the RGB slope. The present data thus suggest that RGB stars are 0.5 ± 0.4 dex more metal poor than the youngest stars in NGC 6822. If the dominant RGB population has an age of 3 Gyr, then these data indicate that Δ[Fe/H]/Δt = −0.2 ± 0.1 dex Gyr⁻¹ since intermediate epochs in the disk of NGC 6822.

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