DEEP ALTAIR + NIRI IMAGING OF THE DISK AND BULGE OF M31

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ABSTRACT

Deep J, H, and K' images, recorded with the ALTAIR adaptive optics system and NIRI imager on Gemini North, are used to probe the stellar content of the disk and bulge of the Local Group galaxy M31. With an FWHM near 0'08 in K, these are the highest angular resolution near-infrared images yet obtained of this galaxy. One field samples the outer disk of M31 at a galactocentric distance of roughly 62' along the major axis. The mean metallicity in this field is close to that of the metal-rich globular cluster NGC 6528, and no stars with [Fe/H] < −0.7 are detected. Another field, located on the major axis 9' from the galaxy center, contains a roughly equal mix of disk and bulge stars. The red giant branch (RGB) in this field is redder than that of NGC 6528, although it is argued that reddening internal to M31 may be significant in this region of the galaxy. The remaining two fields, located at projected galactocentric distances of 2' and 4', are dominated by bulge stars. The RGB tip occurs between K = 17.0 and 17.2, and the color of the RGB in the field closest to the center of M31 is consistent with that of NGC 6528. After accounting for random photometric errors, the upper RGB in each field has a width on the (K,J − K) color-magnitude diagrams that is consistent with a ±0.5 dex dispersion in [Fe/H], in rough agreement with what is seen in other disk and spheroid fields in M31. The number of bright asymptotic giant branch (AGB) and RGB stars also scales with the r-band surface brightness in all four fields. Thus, we conclude that the stellar content does not change markedly from field to field and that the photometric properties of the brightest AGB stars in the two innermost fields are not affected significantly by crowding. The brightest star has $M_K = -8.6$ and $M_{bol} = -5.2$, although this may not be a reliable measure of the AGB-tip brightness because of photometric variability. A population of very bright red stars, which we identify as C stars, are seen in the three fields that are closest to the center of M31. The spatial distribution of these objects suggest that they are well mixed throughout this part of M31, and thus they likely did not form in a compact region near the galactic nucleus but more probably in the inner disk. We speculate that these C stars may be the most luminous members of the intermediate-age population that has been detected previously in studies of the integrated spectrum of the central regions of M31.

Key words: galaxies: individual (M31) — galaxies: stellar content — stars: AGB and post-AGB — stars: carbon

1. INTRODUCTION

In recent years considerable effort has been dedicated to determining when the morphological characteristics of galaxies were set in place. In the case of spiral galaxies a major issue is the relative timescale of bulge and disk formation (e.g., Bouwens et al. 1999). One class of model argues that bulges form early on, prior to the creation of stable disks, as the result of mergers or a monolithic collapse. Indeed, cosmological models that assume a cold dark matter (CDM) dominated universe predict that large galaxies formed through the accretion of small gas-rich protogalactic fragments. These fragments were likely short lived, as they were consumed in major mergers that altered morphologies through kinematic heating and spurred large-scale episodes of star formation (e.g., Somerville et al. 2001). Given the chaotic state of the early universe and the difficulty of maintaining stable disks in such environments (e.g., Weil et al. 1998), it might be anticipated that bulges were the first long-lived structures to form in the systems that would eventually become spiral galaxies. This is consistent with the relative colors of bulges and disks in the Hubble Deep Field (Abraham et al. 1999) and with the age of the Galactic bulge (e.g., Feltzing & Gilmore 2000; Ortolani et al. 1995).

At the other extreme are models in which disks formed first and bulges are the result of secular processes involving disk material. The motion of gas in the disk can lead to the
formation of spheroidal structures. Bars, which may form when gas is channeled toward the central regions of a galaxy, are key elements in this process. The bar transports angular momentum from the central regions of the galaxy to larger radii, so that stars formed in the bar are scattered out of the disk to form a spheroidal structure when the bar buckles (e.g., Friedli & Benz 1995). Stars that form in the inner regions of a galaxy in the absence of a bar may also be scattered into the surrounding bulge by interactions with molecular clouds (Kim & Morris 2001). Consequently, the inner bulges of systems that are experiencing, or did experience, nuclear star formation might contain a diffuse population of intermediate-age stars that did not form in situ.

Evidence that material originally in the disk contributes to the formation of bulges comes from the structural properties of the spheroids in late-type galaxies. Rather than following an $R^{1/4}$ profile, which is the expected signature of violent relaxation, the central spheroids of late-type spiral galaxies follow Sérsic profiles with exponents that are indicative of a more leisurely formation process (e.g., Balcells et al. 2003; Courteau et al. 1996; Andredakis et al. 1995). It might also be anticipated that the stellar contents of bulges will show a morphological dependence if they are built up by secular processes, in the sense that the luminosity-weighted ages of bulges will become younger as one moves to later morphological types. Nevertheless, some exponential bulges have colors that are similar to those of bulges that follow $R^{1/4}$ light profiles (Carollo et al. 2001), suggesting that secular evolution may have occurred early on but was subsequently curtailed. The development of bulges from disk material may also affect the large-scale properties of disks, as the mixing caused by bars will smooth out preexisting abundance profiles in the disk (e.g., Friedli & Benz 1995).

The monolithic collapse and secular evolution models of bulge formation make different predictions about the properties of bulges and their component stars. If bulges form early on in violent collapse episodes, they will be made up of old stars. Metallicity gradients that are the signatures of dissipation should also be present. Finally, the chemical contents of stars formed in such a manner will show signatures of rapid enrichment. On the other hand, bulges that are assembled solely from secular processes will be comprised of young or intermediate-age stars. There may be an age gradient, in the sense that the youngest stars are located closest to the disk plane. The chemical compositions of stars in a bulge assembled in such a way will also show the signatures of a slow enrichment history.

As noted by Bouwens et al. (1999), reality likely falls somewhere between the extremes defined by the monolithic collapse and secular evolution models. Indeed, bulges almost certainly do not evolve in isolation, and there are observational indications that the evolution of bulges and disks are coupled even long after the bulge is in place. There is a high incidence of distinct nuclear sources in the central regions of nearby bulges, which have spectrophotometric properties that differ from those of the surrounding bulge and show evidence of recent star formation (e.g., Boker et al. 1999, 2002; Carollo et al. 2002). Reservoirs of cool gas must be present near the centers of these galaxies, and the surrounding disks are a likely source of this material. This interplay between disks and bulges has been ongoing for some time, as central blue knots are seen in many disk galaxies at intermediate redshifts (Ellis et al. 2001).

The observational challenges inherent to studies of very distant systems can make it difficult to use them to distinguish between the various processes that affect bulge evolution (e.g., Bouwens et al. 1999). However, the interplay between disks and bulges has observational consequences in nearby spiral galaxies, and thus these systems are key laboratories for testing models of bulge evolution. Studies of the resolved stellar contents in the bulges of nearby galaxies can be used to search for the young and intermediate-age stars that are the expected signatures of secular processes. Moreover, if stars on the red giant branch (RGB) are resolved, it may be possible to search for the abundance gradients that are the expected signatures of a dissipational collapse.

As the closest external spiral galaxy, M31 is an obvious target for detailed study. There are hints that, like many other nearby systems, the central regions of M31 may have experienced star formation in the not-too-distant past. The colors of the nucleus differ from those of the surrounding bulge (King et al. 1995; Davidge et al. 1997a; Brown et al. 1998; Lauer et al. 1998), suggesting a distinct stellar content such as might remain after the termination of star formation during the last few billion years. There are also spectroscopic signatures of a central young and/or intermediate-age population (e.g., Bica et al. 1990; Davidge 1997; Sil’chenko et al. 1998), although a population of resolved intermediate-aged stars has yet to be detected in the inner regions of M31. In fact, the brightest red stars are well mixed throughout the inner bulge and thus likely formed with the main body of the bulge (Davidge 2001). In addition, the brightnesses and densities of luminous asymptotic giant branch (AGB) stars in the bulge of M31 are similar to those in systems as disparate as M32 and NGC 5128, further supporting the notion that they come from an old population (Davidge 2002). The RGB of the M31 bulge has a color that is consistent with a near-solar metallicity (Jablonka et al. 1999; Stephens et al. 2001), although the RGB tip may be depressed with respect to larger galactocentric distances (Jablonka et al. 1999). This latter result is counter to what would be expected if metallicity decreases with increasing galactocentric distance but could be indicative of an age gradient.

Additional hints into the star formation history of the central regions of M31 come from studies of stars in the disk of the galaxy. Morrison et al. (2004) find a population of globular clusters in M31 that have disk kinematics and span a range of metallicities, suggesting that a stable disk was in place at very early epochs, so that secular interactions between the disk and bulge may have started early on. Young and intermediate-age stars are seen at moderate to large galactocentric distances (e.g., Richter et al. 1990; Davidge 1993; Brewer et al. 1995; Cuillandre et al. 2001; Sarajedini & Van Duyne 2001; Ferguson & Johnson 2001), and there was large-scale star formation throughout much of the disk up to 1 Gyr in the past (Williams 2002). However, star formation at present appears to be restricted to the spiral arms, where the star formation rate has not changed during the past gigayear (Williams 2002). The metallicity distribution is remarkably similar over a large range of galactocentric distances, peaking near $[\text{Fe/H}] = -0.6$, with only a very modest number of stars with $[\text{Fe/H}] < -1.5$, even in fields that sample the halo (e.g., Bellazzini et al. 2003). Finally, there have been interactions between M31 and its companions (e.g., Saito & Iye 2000; Choi et al. 2002; Ferguson et al. 2002), which have probably influenced the star formation history of M31 and may have triggered flows of gas into the central regions of the galaxy.

Are there spatially resolved young or intermediate-age stars in the innermost regions of M31? Do studies of the photometric properties of resolved RGB stars reveal signs of a metallicity
gradient in the inner spheroid, as predicted if the bulge experienced a dissipational collapse? In the present study, deep $J$, $H$, and $K'$ images obtained with the ALTAIR adaptive optics (AO) system+NIRI imager on Gemini North (GN) are used to probe the age and metallicity distributions in four M31 fields.

The near-infrared is an important wavelength region for studies of this nature. The photometric properties of very red stars at visible wavelengths are affected by line blanketing, and one consequence is that the upper RGB of stars with near-solar metallicities slumps over on visible wavelength color-magnitude diagrams (CMDs). This makes it difficult to detect the most metal-rich upper RGB stars, and thus the mean metallicity of the RGB may be underestimated. Line blanketing also causes the AGB to be a near-horizontal sequence on CMDs constructed from images with wavelengths shortward of 1 $\mu$m (e.g., Fig. 5 of Richer et al. 1990). However, the AGB forms a sequence that is closer to vertical on near-infrared CMDs (e.g., Davidge 2000a), thereby making it easier to resolve AGB stars in crowded fields and identify the AGB tip. There is also a well-calibrated relation between the slope of the RGB and metallicity in the near-infrared (e.g., Ferraro et al. 2000; Kuchinski et al. 1995). Finally, interstellar extinction is less of a concern in the infrared, reducing complications caused by the nonuniform distribution of dust throughout the M31 disk (e.g., Cuillandre et al. 2001; Williams 2002).

The fields discussed here sample a range of stellar densities, from the outer disk, where the incidence of crowding is negligible, to a distance of only 2' from the galaxy center, where crowding is a significant concern (e.g., Davidge 2001; Stephens et al. 2001). Three of the fields are dominated by bulge stars, while the fourth is dominated by disk stars. With an angular resolution of 0.08 FWHM in $K'$, which corresponds roughly to 0.3 pc at the distance of M31, these are the highest angular resolution near-infrared images yet obtained of this galaxy.

The paper is structured as follows. Details of the observations, the data reduction procedures, and the photometric measurements are discussed in § 2. In §§ 3 and 4 the photometric properties of stars in the disk and bulge fields are discussed, while in § 5 the issue of crowding is addressed. A summary and discussion of the results follows in § 6.

2. OBSERVATIONS, REDUCTIONS, AND PHOTOMETRIC MEASUREMENTS

2.1. Observations

The data were recorded during the night of 2003 November 18–19 (UT) with the ALTAIR AO system and NIRI imager on GN as part of the system verification program for ALTAIR. ALTAIR is a natural guide-star AO system, the key elements of which are a 177 element deformable mirror (DM), conjugated to an altitude of 6.5 km above the Mauna Kea summit, and a 12 × 12 Shack-Hartmann wave-front sensor (WFS). Herriot et al. (2000) give a complete description of ALTAIR. NIRI is the facility infrared imager on GN, and this instrument is described in detail by Hodapp et al. (2003). The f/32 camera was used for these observations, and thus each pixel on the 1024 × 1024 InSb detector subtends 0.022 on a side, while the total imaged field is 22.5′ × 22′.5.

The target fields were selected on the basis of the availability of a guide star with $R < 13$, which is the brightness that will allow ALTAIR to provide the maximum correction during typical observing conditions. Four fields in M31 that sample regions with very different stellar densities were observed through $J$, $H$, and $K'$ filters. Table 1 lists (1) the field names used throughout this study, (2) the coordinates and Guide Star Catalog identification numbers of the guide stars, (3) the angular distance from the center of M31, (4) the $r$-band disk and bulge surface brightnesses for each field based on the Kent (1989) small bulge model, and (5) the exposure times for each field. Walterbos & Kennicutt (1988) compute an effective radius of 2.0 kpc for the M31 bulge, which corresponds to 9′, and two of the four fields fall within this radius. The guide star for bulge 1 is not in the Guide Star Catalog because of its close proximity to the center of the galaxy.

A four-point square dither pattern, which was 4′ on a side, was employed in $J$ and $H$, while a five-point dither pattern, which was the same pattern used in $J$ and $H$ but with an extra point in the middle, was used in $K'$. The uncorrected image quality while these data were recorded, calculated from data supplied by the ALTAIR WFS, ranged between 0′45 and 0′80 FWHM at visible wavelengths. The corrected image quality at a few arcseconds distance from the AO reference star is typically 0′08 FWHM in $K'$ and 0′10 FWHM in $J$ and $H$.

2.2. Data Reduction

The data were reduced using a standard pipeline for infrared observations. The initial steps in the reduction sequence were (1) the subtraction of a dark frame, (2) the division by a flat-field frame, (3) the removal of the DC sky level on a frame-by-frame basis, and (4) the removal of interference fringes and the thermal signatures of warm objects along the optical path. The calibration frame used in the last step was constructed by median-combining sky-subtracted images of all M31 fields.

The processed images were registered to correct for dither offsets and then median-combined to suppress bad pixels and

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### Table 1

| Field Name       | R.A. (J2000) | Decl. (J2000) | GSC No.   | $R_{GC}$ (arcmin) | $\mu_{disk}$ | $\mu_{bulge}$ | Exposures (s) |
|------------------|--------------|---------------|-----------|-------------------|--------------|---------------|---------------|
| Disk 1............| 00 39 13.3   | +40 29 13.3   | 02788-0207 | 61.74             | 22.2         | ...           | 20 × 40 ($J + H$) |
| Disk 2............| 00 43 21.7   | +41 21 55.2   | 02805-0213 | 9.09              | 20.8         | 20.7          | 24 × 40 ($J + H$) |
| Bulge 2...........| 00 42 50.9   | +41 12 31.4   | 02801-0208 | 3.83              | 20.5         | 19.2          | 27 × 40 ($K$)    |
| Bulge 1...........| 00 42 33.5   | +41 15 50.1   | ...        | 2.05              | 20.2         | 18.1          | 10 × 40 ($K$)    |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
cosmic rays. A small number of exposures in which the image quality was noticeably poorer than average were not included when creating the combined images. Finally, the combined images of each field were trimmed to the area of common exposure time, which is typically $17''5 \times 17''5$. The final $K$-band images of the disk 1 and bulge 1 fields, which have the lowest and highest stellar densities in the current sample, are shown in Figures 1 and 2.

### 2.3. Photometric Measurements

Stellar brightnesses were measured with the point-spread function (PSF)–fitting program ALLSTAR (Stetson & Harris 1988), using PSFs and stellar coordinates obtained with tasks in DAOPHOT (Stetson 1987). A single spatially nonvarying PSF, typically obtained from 30 to 60 stars, was constructed for each field + filter combination. Anisoplanicity distorts the PSF near the edge of some of our images (e.g., McClure et al. 1991), and only those portions of the data sets that were deemed to have stable PSFs, as determined from a visual inspection of the sharpness and shape of the PSF, were considered for photometric investigation. In $J$ the maximum radius for PSF stability was roughly $5''$ from the guide star, while in $H$ this radius was typically $6''-7''$. The PSF was stable over an even larger portion of the field in $K$. The disk 1 data were recorded during exceptionally good conditions, and there is no sign of anisoplanicity in these data. Consequently, photometry was done over the entire field. No attempt was made to do photometry within $2''$ of the reference star in any field, as the PSF wings of this very bright object hinder the detection of faint stars.

The photometric measurements used in this study were made by T. J. D. An independent set of photometric measurements was made by K. A. G. O., also using DAOPHOT. The two sets of calibrated photometry agree within the uncertainties, lending confidence to the photometric measurements.

The photometric calibration was set using observations of standard stars from Hawarden et al. (2001) and Hunt et al. (1998). The standard deviation of the individual standard star measurements about the final zero points, obtained with an aperture having a 25 pixel radius so as to match the PSF radius used for the M31 photometry, is $\pm 0.1$ mag in all three filters. Aperture corrections were measured from the PSF stars in each frame. The presence of faint, unresolved stars introduces uncertainties in these measurements that depend on the stellar density of the field in question. We estimate that the aperture corrections in disk 1, disk 2, and bulge 2 have uncertainties of a few hundredths of a magnitude, while in bulge 1 the aperture correction may have an uncertainty of $\pm 0.1$ mag.

The photometric calibration was checked using the published Two Micron All Sky Survey (2MASS) brightnesses of the AO guide stars in bulge 1, bulge 2, and disk 2; this was not possible for disk 1, as the AO guide star was not detected by 2MASS. The central cores of the guide stars are saturated in the images, and thus the total brightness was estimated from the wings of the PSF. For bulge 1 and 2 the estimated brightness of the guide star agrees with that measured by 2MASS to within a few hundredths of a magnitude. However, for disk 2, which has the brightest and hence most heavily saturated AO reference star, there is a 0.25 mag difference in $K$ between the brightness measured from the ALTAIR data and that measured by 2MASS, in the sense that the ALTAIR brightness is the fainter of the two. Given that (1) the bright stellar contents in these fields scale well with surface brightness ($\S$ 5) and (2) the ALTAIR and 2MASS brightnesses of the guide stars in bulge 1 and 2 are in

![Fig. 1.—Final $K'$ image of the disk 1 field. The displayed field is roughly $17''5 \times 17''5$.](image)
good agreement, we suspect that the AO guide star for disk 2 is a photometric variable.

2.4. Artificial-Star Experiments

Artificial-star experiments were run to determine sample completeness, estimate the uncertainties introduced by photon statistics and crowding, and assess systematic effects in the photometry. The artificial stars were created using the PSFs constructed for the photometric analysis, and thus these experiments do not include the effects of anisoplanicity. The artificial stars were distributed randomly throughout the frames, avoiding the high surface brightness region immediately surrounding the AO guide stars. The stars were assigned colors \((H - K = 0.3\) and \(J - K = 1.2\)) and brightnesses \((K\) between 16 and 21) appropriate for AGB and RGB stars in M31 and were distributed in brightness according to a power-law luminosity function (LF) with exponent 0.2. Between 200 and 240 stars were added to each frame over two runs, with a minimum of 10 stars per brightness bin. This number of stars per run was selected to prevent artificially increasing the level of crowding at the faint end in each simulation. While the number of artificial stars used in this study is modest, it is still sufficient to assess the extent of blending and determine the brightness at which sample incompleteness becomes significant in each data set (see below).

The completeness fractions of stars detected in both \(H\) and \(K\), \(C_{HK}\), as well as the mean difference between the actual and measured \(K\) brightnesses, \(\Delta K\), and the standard deviation about \(\Delta K\), \(\sigma_K\), are shown in Figure 3. The difference between the actual and measured brightnesses for all of the recovered artificial stars in the two most crowded fields, bulge 1 and 2, is shown as a function of \(K\) in Figure 4. As \(C_{HK}\) drops \(\Delta K\) and \(\sigma_K\) increase, and the magnitude at which sample incompleteness reaches 50% is correlated with field surface brightness, which measures the degree of crowding. \(\Delta K\) is of particular interest as it monitors systematic effects in the photometry. In low-density environments, systematic errors in stellar brightnesses become significant only when statistical errors imposed by the night sky level and integration time become large, as faint sources that coincide with positive peaks in the sky noise spectrum are preferentially detected. The situation is different for very crowded environments, where systematic errors due to crowding, including blending, may occur well above the limit imposed by photon statistics. It should be noted that in crowded fields the systematic effects on colors, especially those spanning small to intermediate wavelength intervals, will likely be smaller than in single-filter measurements, as the photometry in both filters is affected by crowding by roughly the same amount.

In both disk fields and bulge 2 \(\Delta K\) and \(\sigma_K\) only depart significantly from the values defined at the bright end when \(K > 20\), although it is evident from Figure 4 that a modest fraction of objects in bulge 2 with \(K = 19\) may be blends of fainter objects. That \(\Delta K\) and \(\sigma_K\) in these fields are near 0 over much of the brightness range explored by the artificial-star experiments suggests that crowding and blending is not a
factor in these fields. However, the situation is different in bulge 1, which is the most crowded field. In this field, $\Delta K < 0.1$ mag when $K < 18.5$, while $\sigma_k$ grows quickly when $K > 19$.

A modest fraction of objects in bulge 1 at the bright end are likely blends. Indeed, of the 45 artificial stars with $K < 18$, three were recovered with brightnesses that exceed the actual values by at least 0.5 mag, indicating that they were blended with stars of similar brightness. The frequency of such blends is thus $3/45 = 0.067 \pm 0.02$, where the quoted errors are 1 $\sigma$ uncertainties.

3. RESULTS: DISK 1

Disk 1 differs from the other fields observed with ALTAIR in that (1) the stellar density is low, so that crowding is not an issue, and (2) the stellar content is dominated by disk stars. The $(K, J - K)$ and $(K, H - K)$ CMDs of stars in disk 1 are plotted in the left-hand panels of Figures 5 and 6. The number of stars plotted in each CMD is stated in each panel. Given the modest number of bright giants detected in this field, only limited conclusions can be drawn from these data.

The RGB in disk 1 is wider than what is expected solely from the photometric errors predicted from the artificial-star experiments. This is demonstrated in Table 2, where the standard deviations in $H - K$ and $J - K$ for stars with $K$ between 17.5 and 18.5, which corresponds roughly to the top 1 mag of the RGB, listed in columns (2) and (4), are compared with the dispersions predicted from the artificial-star experiments, which are listed in columns (3) and (5). An $F$-test indicates the observed and predicted dispersions for disk 1 differ well in excess of the 2 $\sigma$ significance level.

A number of factors likely contribute to the broadening of the RGB, including anisoplanicity, differential reddening, and the dispersion in mean metallicity that is seen throughout the disk and halo of M31 (Bellazzini et al. 2003). The latter may dominate. In fact, the metallicity distribution functions (MDFs) constructed by Bellazzini et al. (2003) have an approximate standard deviation of $\pm 0.5$ dex in [Fe/H], and this introduces a dispersion of $\pm 0.1$ mag in $J - K$ near the RGB tip (Ferraro et al. 2000). The result of subtracting in quadrature the scatter due to photometric errors from the observed dispersion in $J - K$ is shown in the last column of Table 2. This...
“residual” scatter is close to that predicted from a ±0.5 dex dispersion in metallicity.

While the \((K, H - K)\) CMD goes considerably deeper than the \((K, J - K)\) CMD, \(J - K\) is much more sensitive to metallicity than \(H - K\), and thus the \((K, J - K)\) CMD is used to investigate the metallicity of stars in this study. The left-hand panel of Figure 7 shows the \([M_K, (J - K)_0]\) CMD of disk 1, assuming a distance modulus of 24.4 (van den Bergh 2000), and \(E(B - V) = 0.1\) for foreground material (Burstein & Heiles 1984). These values are used throughout the paper. The reddening law from Rieke & Lebofsky (1985) was adopted to compute \(A_K\) and \(E(J - K)\). Also shown on Figure 7 are the RGB loci of the globular clusters 47 Tuc (\([\text{Fe}/\text{H}] = -0.8\)) and NGC 6528 (\([\text{Fe}/\text{H}] = 0.0\)), based on the RGB colors listed in Table 2 of Ferraro et al. (2000); the cluster metallicities are taken from the Harris (1996) database.

Inspection of Figure 7 suggests that disk 1 is dominated by relatively metal-rich stars, with a mean \([\text{Fe}/\text{H}]\) close to that of NGC 6528. The MDF is evidently skewed to high values, as no stars significantly more metal-poor than 47 Tuc have been detected, although with only a modest number of stars in the CMD, even a population of giants that are more metal-poor than 47 Tuc and account for \(\leq 10\%\) of the total number of stars may be missed because of small-number statistics. Nevertheless, the relatively high mean metallicity of the disk 1 field is a robust result, which is consistent with other studies of the outer regions of M31 (e.g., Bellazzini et al. 2003).

The \(K\) LF of disk 1, based on stars that are detected in both \(H\) and \(K\), is shown in Figure 8. Whereas a 0.25 mag binning
interval is used to construct the LFs of the fields closer to the center of M31, the low density of stars in disk 1 necessitates the use of a coarser binning interval. Despite the large error bars in the individual bins, it is evident that the disk 1 LF roughly follows a power law.

Davidge (2000b) used the Canada-France-Hawaii Telescope AO system to investigate the stellar content in the metal-rich globular cluster NGC 6528, which has a metallicity and age that is comparable to that of stars in Baade’s Window (e.g., Momany et al. 2003). A least-squares fit of a power law to the NGC 6528 LF shown in Figure 3 of Davidge (2000b), neglecting the bins containing the horizontal branch and RGB-bump, gives an exponent \( x = 0.21 \). For comparison, Davidge (2001) found that the K LFs of metal-poor globular clusters tend to have \( x = 0.3 \), although there is considerable scatter, with some clusters having exponents similar to that measured in NGC 6528. Given that the RGB in disk 1 has a color consistent with NGC 6528, a power law with \( x = 0.21 \) was fitted to the LF entries with K between 18 and 21, and the result is plotted in Figure 8. The \( x = 0.21 \) power law provides a reasonable fit to the data, although there is considerable scatter due to small-number statistics.

We have not attempted to measure the brightness of the RGB tip in disk 1 because of the modest number of stars. However, it is evident from Figure 7 that the vast majority of the stars in disk 1 have \( M_{\text{bol}} > -4 \) and hence are on the RGB (Ferraro et al. 2000). There is only one star significantly brighter than the RGB tip in disk 1, and this object is likely evolving on the AGB.

An intermediate-age population might be expected in disk 1 given the detection of intermediate-age stars in the halo (Brown et al. 2003) and outermost disk (Ferguson & Johnson 2001) of M31. Unfortunately, the AGB content of disk 1 provides only loose limits on age because of the tiny area sampled by ALTAIR+NIRI coupled with the low surface density of stars. The single bright AGB star has \( M_K = -7.5 \). Models predict that the AGB tip should occur near \( M_K = -7.5 \).

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**Table 2**

| Field Name   | \( \sigma_{\text{Meas}} \) | \( \sigma_{\text{Art}} \) | \( \sigma_{\text{Res}} \) |
|--------------|------------------------------|--------------------------|--------------------------|
| Disk 1       | ±0.14                        | ±0.01                    | ±0.10                    | ±0.04                    | ±0.09                    |
| Disk 2       | ±0.09                        | ±0.02                    | ±0.16                    | ±0.04                    | ±0.15                    |
| Bulge 2      | ±0.11                        | ±0.03                    | ±0.13                    | ±0.07                    | ±0.11                    |
| Bulge 1      | ±0.11                        | ±0.06                    | ±0.22                    | ±0.21                    | ±0.08                    |
in solar metallicity systems with ages in excess of \( \sim 5 \) Gyr (Girardi et al. 2002), and this is consistent with the intrinsic \( K \)-band brightnesses of long-period variables (LPVs) in metal-rich globular clusters (e.g., Frogel 1983). Therefore, on the basis solely of the single bright AGB star detected here, there is no evidence for a population younger than a few gigayears, although this conclusion may change when a larger area near disk 1 is surveyed.

4. RESULTS: THE INNER DISK AND BULGE

4.1. Disk 2

The \((K, H-K)\) and \((K, J-K)\) CMDs of disk 2 are shown in the right-hand panels of Figures 5 and 6, while the \([M_K, (J-K)_0]\) CMD is shown in the right-hand panel of Figure 7. The standard deviations of the colors of stars with \( K \) between 17.5 and 18.5 are listed in Table 2. As in disk 1, the disk 2 RGB is wider than expected from photometric errors alone. The scatter that remains after removing the contribution from photometric errors is broader than in disk 1.

The brightest AGB stars in disk 2 have \( M_K \) between \(-8 \) and \(-8.5 \), and the most luminous star has \( M_{bol} = -5 \). The ridge-line of the RGB in disk 2 is 0.2 mag in \( J-K \) redder than in the disk 1. This difference exceeds the 0.1 mag uncertainty in the photometric calibration and thus suggests a higher mean metallicity for disk 2, as might be expected given the evidence for a radial abundance gradient in the M31 disk (e.g., Blair et al. 1982). However, disk 2 is on the eastern boundary of dust lane D517 (Hodge 1981), and thus reddening internal to M31 may contribute to the red RGB color. The amount of internal reddening could be significant, as globular clusters within a tenth of a degree of disk 2 have \( E(B-V) \) as high as 0.4 (Barmby et al. 2000), which corresponds to \( E(J-K) \sim 0.1 \) mag. Correcting for an internal reddening contribution of this size would bring the RGB locus of disk 2 in Figure 7 into better agreement with that of disk 1.

The \((J-H, H-K)\) two-color diagram (TCD) of stars in disk 2 with \( K < 18 \), which includes the AGB and upper RGB, is shown in Figure 9. The stars form a sequence on the TCD that overlaps the locus of solar neighborhood giants and LPVs in the Magellanic Clouds. The spectral energy distributions (SEDs) of the brightest stars in disk 2 appear to differ from those in disk 1, which are also plotted in Figure 9, in the sense that the stars with the reddest \( H-K \) colors in disk 1 have smaller \( J-H \) colors than stars in disk 2. The near-infrared SEDs of the brightest stars in disk 1 are similar to those of the brightest variables in the old moderately metal-poor globular cluster 47 Tuc, which were investigated at near-infrared wavelengths by Frogel et al. (1981).

The \( K \) LF of disk 2, constructed from stars detected in both \( H \) and \( K \), is shown in the bottom panel of Figure 8. The LF follows a power law at the faint end, and the result of fitting a
power law with exponent $0.21$, on the basis of the LF of RGB stars in the globular cluster NGC 6528 (§ 3), to the data between $K = 18$ and 21 is shown as a dashed line. The fitted relation provides a reasonable match to the data. There is a discontinuity near $K = 17.75$, which corresponds to $M_K = -6.6$ with the adopted foreground reddening, that we identify as the RGB tip. This RGB-tip brightness is $0.1–0.2$ mag fainter than what is seen in the total metal-rich globular clusters studied by Ferraro et al. (2000); correcting for internal extinction of the size discussed earlier would bring the measured RGB-tip brightness into agreement with what is seen in the most metal-rich globular clusters.

Stars on the AGB evolve at a pace that is roughly 4 times faster than stars on the RGB, and in the bottom panel of Figure 8 the power law that was fitted to the disk 2 data has been shifted down the vertical axis by an amount that accounts for this faster evolution. The shifted relation matches the data with $K < 17.75$ within the estimated uncertainties, although the data points fall systematically above the expected AGB sequence.

There is a population of bright stars with $(H - K) > 0.6$, which forms a loose sequence that departs from the giant branch in the $(K, H - K)$ CMD. Objects with similar colors were detected by Stephens et al. (2003) and were classified as LPVs in that study. Luminous LPVs in the LMC with $(H - K) > 0.6$ and $(J - K) > 1.6$ tend almost exclusively to be C stars (Hughes & Wood 1990), and thus we identify the very red objects in disk 2 as C stars. We note that there may be a mild metallicity sensitivity to the critical color for identifying C stars, as only four of the six spectroscopically confirmed C stars above the RGB tip in the SMC, which is roughly a factor of 2 more metal-poor than the LMC, listed in Table 1 of Wood et al. (1983) have $(J - K)_0 > 1.6$, although one of the two “missed” stars has $(J - K)_0 = 1.59$.

The detection of bright C stars is direct evidence of an intermediate-age population in disk 2. In fact, C stars contribute a significant fraction of the total AGB luminosity in disk 2. To estimate the fractional contribution made by C stars to the total light output of stars above the RGB tip, bolometric luminosities were computed for stars with $K < 17.5$ using the relation between the $K$-band bolometric correction and $J - K$ from Bessell & Wood (1984). Using this procedure, we find that the six C star candidates in disk 2 account for $29^\pm8\%$ of the total AGB luminosity. This result is sensitive to the threshold color used to define C stars, and the uncertainty in the ratio quoted above was computed by changing the $H - K$ color threshold by $\pm0.1$ mag, which is the uncertainty in the photometric calibration. The sizeable uncertainties in the contributions made by C stars to the total AGB light notwithstanding, it appears that C stars in disk 2 contribute a larger fraction of the total AGB light than near the center of NGC 205, where C stars account for roughly 10% of the total AGB luminosity (Davidge 2003b).

4.2. Bulge 1 and 2

The $(K, H - K)$ and $(K, J - K)$ CMDs of the fields dominated by bulge stars are shown in Figures 10 and 11. As can be seen from the entries in Table 2, the width of the RGB in bulge 2 is comparable to what is seen in disk 1 and 2. While the giant branch in the $(K, J - K)$ CMD of bulge 1 is broader than in any of the other three fields, because of the larger uncertainties in the photometry arising from the high stellar density,
the residual scatter after accounting for the photometric errors is consistent with what is seen in the other fields.

The $[M_K, (J - K)_0]$ CMDs of the bulge fields are shown in Figure 12. All of the stars in bulge 2 have $M_{bol} > -5$, whereas there are three stars brighter than $M_{bol} = -5$ in bulge 1. After adjusting for foreground reddening and the distance to M31, the ridgeline of the bulge 1 RGB coincides with the RGB of NGC 6528. For comparison, the bulge 2 giant branch falls 0.2 mag in $J - K$ redward of the NGC 6528 sequence, an amount greater than the uncertainty in the photometric calibration. Some of the most heavily reddened globular clusters in M31 are seen in the central regions of the galaxy (Fig. 8 of Barmby et al. 2000), raising the possibility that there may be considerable dust along inner bulge sight lines. If, as indicated by globular clusters in the Barmby et al. (2000) sample, $E(B - V) > 0.4$, the intrinsic $J - K$ colors of the RGB in some regions near the center of M31 may be 0.1–0.2 mag bluer in $J - K$ than observed. If internal extinction of this size is present in bulge 2, the RGB of this field would have an intrinsic color that agrees with the NGC 6528 sequence.

The $K$ LFs of bulge 1 and 2, based on stars detected in both $H$ and $K$, are compared in Figure 13. The dashed lines are power laws with exponent $x = 0.21$, computed from the LF of RGB stars in the globular cluster NGC 6528 (§ 3), that were fitted to the LF entries between $K = 18$ and 20. The dashed line is the fitted sequence shifted down by 80% to show the approximate relation for an AGB population. The power law fitted to the RGB provides a reasonable match to the data at the faint end. A discontinuity is seen in the bulge 2 LF between $K = 17.25$ and 17.50, and the amplitude of the discontinuity is consistent with a transition from a population dominated by first-ascent giants to one dominated by AGB stars. As for bulge 1, the LF departs from the RGB trend near $K = 17.0$, suggesting that the RGB tip in this field is brighter than in bulge 2, although we caution that the artificial-star experiments indicate that a modest fraction of the stars at this brightness may be blends. The relative number of stars brighter than the RGB tip is consistent with a transition from RGB- to AGB-dominated populations. In both fields there is a bin near the RGB tip with star counts that are intermediate between the RGB and AGB sequences, indicating that binning errors may introduce a $\sim 0.1$ mag uncertainty in the RGB-tip measurement. Nevertheless, the RGB-tip brightnesses inferred from the discontinuities in the LFs of both fields correspond to $M_K$ between $-7$ and $-7.5$, with the fainter of these being comparable to the brightness expected for an old, solar metallicity population (Ferraro et al. 2000).

The near-infrared SEDs of sources in bulge 1 and 2 are investigated in Figure 14, which shows the $(J - H, H - K)$ TCD of stars with $K < 18$ in both fields. As might be expected from the CMDs, the near-infrared SEDs of the majority of sources in both fields are consistent with them being late M-type giants. There is also a spray of stars having SEDs that tend to fall below the Magellanic Cloud LPV sequence, in a part of the TCD that is occupied by bright variable stars in the Galactic bulge (Frogel & Whitford 1987).

The color distributions of AGB stars in bulge 1 and 2 appear to differ, in the sense that red stars dominate when $M_K < -7.5$
in bulge 1, while in bulge 2 the majority of stars with $M_K < -7.5$ have $J - K \sim 1.4 \pm 0.1$ and are likely oxygen-rich M giants. However, these differences are not statistically significant. More importantly, both fields contain some stars with $K < 17$ that have $H - K > 0.6$ and $J - K > 1.6$, which we identify as C stars (§ 4.1).

The contribution that C stars make to the total AGB luminosity in bulge 1 and 2 is comparable to that in disk 2. After computing bolometric corrections using the procedure discussed in § 4.1, we find that the six C star candidates in bulge 1 account for $17 \pm 18\%$ of the total AGB light, while the two C stars in bulge 2 contribute $7 \pm 15\%$ of the total AGB luminosity. As in § 4.1, the uncertainties reflect the effect of changing the color threshold for identifying C stars by $\pm 0.1$ mag. Stephens et al. (2003) argued that the number density of very red stars, when normalized to bluer stars, does not change from field to field. The ALTAIR data support this conclusion, although we emphasize that the uncertainties in the fractional C star luminosities are substantial.

5. CROWDING

5.1. The Incidence of Blending in the ALTAIR Data

Blending occurs when two or more stars fall within the same angular resolution element and thus are identified as a single object. In a very crowded field such as bulge 1 it is likely that all resolution elements contain more than one star, but the effect of a very faint source blending with a very bright source has only a minor impact on the photometric properties of the latter. The most common significant blending event involves two stars with comparable brightnesses, in which case an object will be observed that is roughly 0.6 mag brighter than the progenitors, and the artificial-star experiments discussed in § 2.4 indicate that systematic offsets of this size do not become a factor until well below the RGB tip in the two disk fields and bulge 2. Blends do occur at brighter magnitudes in bulge 1, but the majority of stars when $K < 18$ are predicted to be unblended objects.

Stephens et al. (2003) used simulations to investigate the effects of blending in HST NICMOS observations of various fields in M31, and these simulations provide a check on our artificial-star experiments. Stephens et al. (2003) found that crowding is not a factor among the brightest stars in the NICMOS data when the $K$-band surface brightness is greater than 16 mag arcsec$^{-2}$, which corresponds roughly to an $r$-band surface brightness greater than 18.9 mag arcsec$^{-2}$. When the $K$-band surface brightness is less than 16 mag arcsec$^{-2}$, a significant fraction of the sources detected with NICMOS above the RGB tip may be blends, and the peak stellar brightness could be elevated by 0.5 mag in $K$.

The ALTAIR observations have an angular resolution in $K$ that is over a factor of 2 better than that delivered by NICMOS, and thus the incidence of blending will be reduced with respect to the Stephens et al. (2003) data. Indeed, the ratio of the areas of the resolution elements in the ALTAIR and NICMOS data is $(0.08/0.17)^2 = 0.22$. Therefore, on the basis of the Stephens et al. (2003) simulations, blending among the brightest stars should not significantly affect the conclusions drawn from these data until the $r$-band surface brightness is less than
17.3 mag arcsec$^{-2}$; for comparison, the surface brightness in bulge 1 is 18.1 mag arcsec$^{-2}$. This expectation is consistent with the results from the artificial-star experiments for bulge 1 discussed in § 2.4, which indicate that the vast majority of stars with $K < 17$ are not blends.

5.2. Comparisons with the Disk 1 and HST NICMOS Data

Comparisons between the four fields observed with ALTAIR provide direct checks on the extent of crowding. Disk 1 is of particular interest, as crowding is not an issue in this part of M31. If it is assumed that the stellar contents in all four fields are similar then, if the upper RGB content is not affected by crowding, the number density of stars near the RGB tip should scale with surface brightness. This issue is investigated in Figure 15, where the $K$-band LFs of disk 2 and both bulge fields are compared with the LF of disk 1. The four fields have very different stellar densities, and the number counts of the fields close to the center of M31 were scaled down to match the stellar density in disk 1 using Kent’s (1987) $r$-band surface brightness measurements. When normalized in this manner, the number counts in disk 2 and bulge 2 agree with the disk 1 data, indicating that blending does not affect the data for these fields. As for bulge 1, the LF of this field consistently falls above that of disk 1, although in most instances the difference is significant at only the 1 σ level.

Additional insights into crowding in the ALTAIR observations can be gleaned from comparisons with other data sets. The NICMOS data from Stephens et al. (2003) are of particular interest, as these have an angular resolution approaching that of the ALTAIR data and sample fields spanning a range of stellar densities. In fact, despite significant differences in angular resolution and pixel sampling, we find the same peak brightnesses for the RGB as measured from the NICMOS data. In particular, Stephens et al. (2003) find that the RGB tip occurs near $M_K = -7$, with $(J - K)_0 \sim 1.2$, and this is roughly consistent with what is seen in the ALTAIR observations. Stephens et al. (2003) also find that the brightest stars have $M_K$ between $-8$ and $-8.5$, and this peak brightness is similar to what is seen here.

A more rigorous test of crowding is to compare the number densities of fainter AGB stars and stars on the RGB, where the incidence of blending is expected to be greater than on the upper AGB, in the Stephens et al. (2003) and ALTAIR data. This is done in Figure 16, where the $K$-band LFs of bulge 1 and 2 are compared with the NIC2 $K$-band LFs of fields F1, F174, and F177, which have the highest stellar densities examined by Stephens et al. (2003). As in previous comparisons, differences in stellar density have been removed using the Kent (1987) $r$-band surface brightness measurements. When scaled in this manner, the stellar contents of F1, F174, and F177 are in good agreement, although there is scatter amounting to a few tenths of a dex above the RGB tip. The surface brightnesses of F1 and F174 differ by almost 1 mag arcsec$^{-2}$, and the excellent agreement between the LFs of these fields in Figure 16 suggests strongly that blending is not a major factor at the bright end of the NICMOS data.

![Figure 12](image-url)
Fig. 13.—$K$ luminosity functions of the bulge fields. The solid line shows the LF corrected for incompleteness, while the dotted line shows the raw number counts. The quantity $n_{0.25}$ is the number of stars in the field per 0.25 mag interval in $K$. The error bars show the 1σ uncertainties due to Poisson statistics, as computed by Gehrels (1986), added in quadrature to the uncertainties in the completeness corrections, computed using binomial statistics. The dashed line shows a power law with exponent 0.21, computed from the LF of RGB stars in the globular cluster NGC 6528, that has been fitted to the LF entries with $K$ between 18 and 20. The dash-dotted line shows this same power-law relation, but with the y-intercept decreased by 80%, to approximate the trend expected for stars evolving on the AGB. Note that (1) the RGB tip in bulge 2 appears to be 0.25–0.50 mag fainter than in bulge 1, and (2) the numbers of very bright stars in both fields are consistent with evolution on the AGB.

Fig. 14.—($J − H$, $H − K$) two-color diagram of stars in bulge 1 (open squares) and 2 (filled squares). Only stars with $K < 18$ are plotted to reduce scatter and clutter, and the colors have been corrected only for foreground reddening. The solid line shows the locus of solar neighborhood giants from Bessell & Brett (1988), while the dashed line shows the locus of LPVs in the SMC and LMC based on data from Wood et al. (1983, 1985). The dotted line shows the portion of the TCD occupied by the bright variable stars V1, V2, and V3 in 47 Tuc, based on Fig. 7 of Frogel et al. (1981).

Fig. 15.—$K$ LFs of the disk 2, bulge 2, and bulge 1 fields (dashed lines), compared with the $K$ LF of disk 1 (solid line). The disk 2, bulge 1, and bulge 2 LFs have been scaled to match the density of stars in disk 1 using $r$-band surface brightness measurements from Kent (1987). The quantity $n_{0.5}$ is the number of stars per 0.5 mag interval in disk 1. The error bars show the 1σ uncertainties due to Poisson statistics, as computed by Gehrels (1986), added in quadrature to the uncertainties in the completeness corrections, computed using binomial statistics. Note that the disk 1 LF matches that of disk 2 and bulge 2 at the 1σ level over a wide range of brightnesses, suggesting that the number of blends in the disk 2 and bulge 2 fields are small. While the bulge 1 LF typically also agrees with the disk 1 LF within the 1σ level, the bulge 1 measurements fall systematically above those in disk 1.

Fig. 16.—$K$ LF of bulge 1 and 2 (solid lines) compared with the LFs of Stephens et al. (2003) F1 (dashed line), F174 (dash-dotted line), and F177 (dotted line). The values of $n_{0.25}$ are the number of stars per 0.25 mag interval in bulge 1 and 2. The error bars show the 1σ uncertainties due to Poisson statistics, as computed by Gehrels (1986), added in quadrature to the uncertainties in the completeness corrections, computed using binomial statistics. The Stephens et al. (2003) data have been scaled to account for differences in (1) surface brightness, using the $r$-band measurements from Kent (1987), and (2) area covered.
The bulge 2 LF is in good agreement with the NICMOS measurements over most of the brightness range considered. While the bulge 1 data consistently falls some 0.3–0.4 dex above the LFs of the NICMOS fields, this is likely not a consequence of crowding. The artificial-star experiments indicate that blends may account for ~10% of sources in bulge 1 at $K = 17$, and the offset between the LFs of bulge 1 and the other fields in Figure 16 is greater than this. More importantly, F1 has a higher surface brightness than bulge 1, and it was observed with a coarser angular resolution. Therefore, if blending is a factor in any of the data sets shown in Figure 16, it will be F1 that will be most affected, and this is clearly not the case. It is also worth noting that the bulge 1 and the Stephens et al. (2003) data are in good agreement at the faint end, which is where differences due to blending should be most apparent. We suspect that the elevated star counts at the bright end of bulge 1 may be due to spatial fluctuations in the bright content along the line of sight.

In summary, the comparisons in Figures 15 and 16 indicate that the majority of objects in the ALTAIR data are not affected by crowding.

6. DISCUSSION AND SUMMARY

Near-infrared images with angular resolutions approaching the diffraction limit of the 8 m GN telescope have been used to investigate the photometric characteristics of bright evolved stars in the bulge and inner disk of M31. These are the highest angular resolution images yet obtained of M31 at these wavelengths, and the photometric measurements of the brightest red stars are not affected by blending, even in the field that is closest to the center of the galaxy (§ 5). Thus, these data provide unique insights into the stellar content in the central few arcminutes of M31.

6.1. Stellar Content Trends in the Disk and Bulge of M31

Bellazzini et al. (2003) found a remarkable similarity in the metallicity properties of RGB stars in a number of M31 fields that (1) sample a range of galactocentric radii and (2) are well outside of the bulge. The data discussed in the present paper extend field-to-field comparisons of RGB properties to smaller, bulge-dominated, galactocentric radii. Indeed, the galactocentric radius of bulge 1 is an order of magnitude smaller than the field closest to the center of M31 studied by Bellazzini et al. (2003).

In §§ 3 and 4 it is demonstrated that the RGBs of disk 1 and bulge 1 have $J - K$ colors that are consistent with the RGB of the metal-rich globular cluster NGC 6528, while the RGBs of disk 2 and bulge 2 have $J - K$ colors that are redder than the NGC 6528 sequence. Before discussing this result further, it should be noted that other colors give similar results. In particular, we have compared the $(H, J - H)$ CMDs of the four fields observed with ALTAIR with fiducial globular cluster sequences from Table 6 of Valenti et al. (2004). The RGBs of disk 1 and bulge 1 on the $(H, J - H)$ CMDs agree well with the RGB of the metal-rich globular cluster NGC 6440, which has a metallicity that is only slightly lower than that of NGC 6528, while the RGBs of disk 2 and bulge 2 are significantly redder.

The mean metallicities of the four fields observed with ALTAIR, as inferred from the color of the RGB, are likely reliable to no more than a few tenths of a dex. The uncertainty in the photometric calibration is ±0.1 mag, which introduces uncertainties of ±0.3 dex in [Fe/H]. An even greater source of potential error is the patchy dust absorption that occurs throughout the central regions of M31. In § 4.2 it was argued that this introduces uncertainties of 0.1–0.2 mag in the intrinsic RGB colors, with the result that the mean metallicity in each field cannot be estimated to better than a few tenths of a dex.

While the color of the RGB can be affected by uncertainties in the photometric calibration and the mean line-of-sight extinction, this is not the case for the scatter at a given brightness within a particular field. After accounting for the dispersion caused by photometric errors, as predicted by artificial-star experiments, the widths of the upper RGBs of all four fields on the $(K, J - K)$ CMDs are consistent with a metallicity dispersion with a standard deviation ±0.5 dex in [Fe/H]. This is similar to the dispersion detected by Bellazzini et al. (2003) in a large number of fields throughout the disk and halo of M31.

The similarity in stellar content between the four fields observed with ALTAIR is not restricted to metallicity and metallicity dispersion. In § 5.2 it was demonstrated that the $K$-band LFs of the four ALTAIR fields scale with $r$-band surface brightness. In old solar metallicity populations the integrated $r$-band light is dominated by main-sequence stars (e.g., Buzzoni 1989). For comparison, the $K$-band LFs constructed from the ALTAIR data are dominated by stars on the upper RGB and AGB. The comparisons in Figure 15 thus show that the ratio of AGB+RGB stars to main-sequence stars, which is a quantity that is sensitive to age, appears not to change over a range of disk-to-bulge ratios.

In the following subsections the results obtained from the ALTAIR data are discussed in the context of other observations. Given that disks and bulges are structurally distinct entities, the stellar contents of the disk and bulge of M31 are discussed separately. However, the reader is reminded that there are mechanisms that may couple the stellar contents of disks and bulges (e.g., Kim & Morris 2001).

6.1.1. The Disk

That the metallicities of RGB stars in disk 1 and 2 differ by no more than a few tenths of a dex suggests that the metallicity gradient among RGB stars in the disk of M31 must be modest in size, and this conclusion is consistent with some, but not all, studies of the chemical content in M31. For example, Trundle et al. (2002) find that the chemical contents of bright supergiants do not show radial variations in M31, while Bellazzini et al. (2003) find that the abundance distributions of RGB stars in a number of fields are similar. In contrast, Blair et al. (1982) find radial gradients in the abundances of nitrogen and oxygen in M31 H ii regions that are consistent with radial variations in the C- to M-giant ratio when $R_{GC} < 20$ kpc, if changes in this ratio are assumed to be due to metallicity (Brewer et al. 1995).

Radial variations in mean age and metallicity are common in spiral galaxies (e.g., Bell & de Jong 2000), and gradients of this nature were likely imprinted during disk formation. However, as noted in the previous paragraph, there are some indications that mixing may have been highly effective throughout a large portion of the M31 disk, at least among stars with ages comparable to objects on the RGB. What processes could have smoothed population gradients in the disk of M31?

Radial flows of gas and stars in disks can be induced by a number of processes, including spiral density waves (e.g., Casuso & Beckman 2001; Sellwood & Binney 2002), viscosity (Silk 2001; Ferguson & Clarke 2001), galaxy-galaxy interactions (Barnes & Hernquist 1992; Mihos & Hernquist 1996),
dynamical friction (Noguchi 1999, 2000), and the infall of angular momentum–rich gas from the halo (Ferguson & Clarke 2001). The outward movement of gas clouds may drive the age distribution near the disk edge to younger values (Ferguson & Clarke 2001). In fact, intermediate-age populations at large galactocentric distances, possibly related to the disk, are seen in the Sc galaxies NGC 2403 and M33 (Davidge 2003a), as well as in the outer regions of the M31 disk (Ferguson & Johnson 2001).

Of the various mechanisms that might cause mixing, tidal interactions between M31 and its companions are potentially attractive given the evidence that M31 and its satellites have interacted. For example, there is a warp in the H i disk (e.g., Sawa & Sofue 1982), while the star formation history of NGC 205 appears to be coupled with its orbit about M31 (Davidge 2003b). Perhaps most significantly, there are well-defined tidal tails extending from some M31 companions (e.g., Ferguson et al. 2002). However, tidal interactions should also cause mixing of gas, and thus this process does not explain the abundance gradients found by Blair et al. (1982). Clearly, it will be of interest to determine whether RGB stars in other disk systems, such as M81, show evidence for an abundance gradient or are as well mixed as in M31.

6.1.2. The Bulge

The bulge of M31 likely contains a radial metallicity gradient. Davidge (1997) estimated that $\Delta [\text{Fe/H}] / \Delta \log (r) = -0.5$ from a grid of long-slit spectra that mapped the central 1 of M31. This is shallower than what is seen in the outer regions of the bulge of the Milky Way (Minniti et al. 1995; Tiede et al. 1995), although Ramirez et al. (2000) find that the metallicity gradient in the Galactic bulge may flatten in the central few hundred parsecs.

If the gradient measured by Davidge (1997) is assumed to extend to larger radii, then the mean metallicities of bulge 1 and 2 will differ by 0.15 dex. This is likely a lower limit, as the abundance gradient outside of the inner regions of the M31 bulge may steepen, as is the case in the Milky Way (Ramirez et al. 2000). The bulge 1 and 2 data may contain signs of a metallicity gradient in the M31 bulge. In §4.2 it is demonstrated that the RGB tip in bulge 1 appears to the brighter than that in bulge 2. While the artificial-star experiments indicate that some of the stars in bulge 1 near the RGB tip are likely blends, the number of such objects accounts for only ~7% of the total at this brightness (§4.2), and this is clearly not enough to explain the difference in the RGB tips in Figure 13. We further note that the difference in RGB-tip brightness is also not a consequence of small-number statistics, as numerical simulations indicate that only 45 stars are needed on the upper 2.5 mag of the RGB to measure the RGB-tip brightness to within ±0.1 mag (Crocker & Rood 1984), and the upper RGBs of bulge 1 and 2 contain far more stars than this.

A metal-rich population in bulge 1 that is not seen in bulge 2 could explain the difference in RGB-tip brightnesses, as the brightness of the RGB tip in K depends on metallicity, in the sense of becoming brighter and redder with increasing metallicity. The calibration between the K-band RGB-tip brightness and metallicity among globular clusters derived by Ferraro et al. (2000) indicates that a 0.15 dex difference in metallicity would change the RGB-tip brightness by roughly 0.1 mag, and a shift of this nature would bring the bulge 1 and 2 LFs in Figure 13 into better agreement. It should be emphasized that the RGB colors of bulge 1 and 2 are not consistent with this interpretation, although this could be a consequence of reddening internal to M31 (e.g., §4.2). Clearly, spectroscopic observations of individual stars will be the most secure means of measuring metallicities, and integral field spectrographs coupled to adaptive optics systems, such as ALTAIR+NIFS on Gemini North, will be required to overcome crowding in the high stellar density fields near the center of M31.

6.2. The Bright AGB Content Near the Center of M31 and the Presence of C Stars

One of the goals of photometric surveys of nearby spiral galaxies is to probe the star formation histories of their pressure and rotationally supported components, as this will provide insight into when their global morphological characteristics were imprinted. In the case of the Milky Way, the relative age of the disk and bulge is still a matter of debate. Studies of the main-sequence turnoff in the Galactic bulge indicate that it has an age that is similar to that of the majority of globular clusters (Feltzing & Gilmore 2000; Kuijken & Rich 2002; Zoccali et al. 2003). However, the age of the Galactic disk is less certain. Binney et al. (2000) conclude that the solar neighborhood contains stars that are at least as old as the oldest globular clusters, although studies of white dwarfs suggest an age of only 8 Gyr for the solar disk (Leggett et al. 1998; but see also Hansen 1999).

Peak AGB brightness offers one means of investigating the ages of stars near the center of M31, although there are significant problems with this statistic as an age indicator. First, the three fields observed with ALTAIR near the center of M31 contain a mixture of bulge and disk stars. Lacking kinematic information for individual objects, the task of isolating pure samples of disk and bulge stars is problematic. Second, the brightness of the AGB peak depends on metallicity as well as age, so there is an age-metallicity degeneracy when interpreting the peak brightness. A young or intermediate-age component that is moderately metal-poor may also be missed if there is an older but more metal-rich population with a brighter AGB tip. Third, efforts to measure the peak brightness of the AGB are complicated by stellar variability. If the brightest AGB stars in the bulge of M31 are LPVs like those in the Galactic bulge, they will have amplitudes of up to ±0.1 mag in K (Glass et al. 1995). In fact, it is likely that the brightest stars imaged in the bulge of M31 at any given time are LPVs near the peak of their light curves, and this can be confirmed with multiperiodic observations, as has been done for M32 by Davidge & Rigaut (2004).

The brightest AGB stars in bulge 1 and 2 have $M_K < -8.5$ and $M_{bol} = -5$ and hence are not different from what is seen in the Galactic bulge (Frogel & Whitford 1987). If these stars are LPVs near the peak of their light curves, they will have a mean brightness $M_K \sim -7.5$. This is consistent with the expected AGB peak brightness in an old solar-metallicity system (Girardi et al. 2002). The peak AGB brightness in the M31 bulge is also comparable to that of the brightest AGB star in the metal-rich globular cluster NGC 6553 (Guarnieri et al. 1997), which has an old age (e.g., Ortolani et al. 1995). These data thus suggest that an old population dominates in the inner regions of M31.

As noted above, peak stellar brightness does not offer an ironclad means of probing age. In fact, there are a number of sources with $M_K < -8$ in bulge 1 and 2 and the disk 2 field that have very red colors, and these provide additional insights into the stellar content near the center of M31 that contradicts the notion that these fields are dominated by an old stellar population. In particular, Hughes & Wood (1990) investigated the near-infrared photometric properties of LPVs in the LMC, and
found that the vast majority of objects with \( J - K > 1.6 \) are C stars; of the three objects in their sample with \( J - K > 1.6 \) that are not C stars, two are very luminous (\( M_{\text{bol}} < -5.5 \)) and have periods in excess of 600 days. Davidge (2003b) used \( H - K \) and \( J - K \) colors to identify C stars in NGC 205 based on color criteria from Hughes & Wood (1990) and recovered C stars identified previously by Richer et al. (1984) from narrowband photometry.

Based on the photometric study by Hughes & Wood (1990), we identify objects with \( J - K > 1.6 \) in the ALTAIR CMDs as C stars. These stars tend to have \( M_P \) between \(-7\) and \(-8.5\). Observations indicate that C-star production does not occur in systems with ages in excess of 6 Gyr and that the maximum age for C-star production drops as one moves to higher metallicities (e.g., Cole & Weinberg 2002). Hence, the presence of C stars indicates that there is likely an intermediate-age population in disk 2 and bulge 1 and 2.

The identification of the very red objects in M31 as C stars has potential implications for the bulge and inner disk of the Milky Way, as a population of very red objects is also seen in the \((K, J - K)\) CMD of Baade’s window shown in Figure 17 of Frogel & Whitford (1987). The main stellar sample considered by Frogel & Whitford (1987) consists of M giants that were selected from grism surveys, and only two of the stars identified as M giants have \( J - K > 1.6 \). Both of these objects have spectral types from Blanco et al. (1984), are photometrically variable, and have two \( J - K \) colors listed in Table 1 of Frogel & Whitford (1987). Star 87 (spectral type M8) has \( J - K = 1.59 \) and 1.76, and thus may or may not meet the near-infrared color criterion for C-star status, depending on the epoch of observation. Star 250 (spectral type M7) is clearly more interesting, as it has \( J - K > 2 \) in both measurements; however, it is also one of the faintest stars classified by Blanco et al. (1984) and thus presumably falls near the faint limit of their data.

The remainder of the stars with \( J - K > 1.6 \) in the Frogel & Whitford sample are LPVs from the sample that was observed by Glass & Feast (1982). To the best of our knowledge these objects do not have spectra, presumably because they are relatively faint at visible wavelengths. In fact, the TCD shown in Figure 2 of Frogel & Whitford (1987) indicates that a star with \( J - K = 1.6 \) will have \( V - K \approx 10 \). The LPVs in Figure 17 of Frogel & Whitford (1987) tend to have \( K_0 \) between 6 and 7.5 (i.e., \( M_P \) between \(-7\) and \(-8.5\)), and thus will have \( V_0 \) between 16 and 17.5. After dimming to account for extinction, these stars will have \( V \) between 17 and 18.5.

Azzopardi et al. (1985) conducted a grens survey of Baade’s window and found 15 C stars with \( V \) between 15.5 and 17.5. Azzopardi et al. (1985) argued that these stars are too faint to be C stars associated with the Galactic bulge; however, the arguments given in the previous paragraph indicate that at least some of the objects found by Azzopardi et al. (1985) have \( V \) brightenesses that are consistent with them being very red C stars at the distance of the Galactic bulge. To be sure, some of these objects may be dwarf C stars, which are difficult to identify using spectrophotometric information alone (e.g., Downes et al. 2004). The only ironclad means to confirm the nature of the C stars identified by Azzopardi et al. (1985) is to obtain proper motions for these objects, which would allow their distances to be measured.

6.3. The Nature of Intermediate-Age Stars Near the Center of M31

The detection of intermediate-age stars in the ALTAIR data is perhaps not a surprise. Spectroscopic studies suggest that there is a centrally concentrated young or intermediate-age component in M31 (Bica et al. 1990; Davidge 1997; Sil’chenko et al. 1998). The geometric center of M31 has a very red \( V - K \) color (Davidge et al. 1997a), which may be due to a population of AGB stars that formed during the past gigayear.

Studies of the innermost regions of the Galactic bulge may provide clues about the nature of the central regions of M31. Contrary to expectations (e.g., Figer et al. 2000), star formation occurs near the center of the Galaxy. There is a cluster of young stars around Sgr A* (Lebofsky et al. 1982; Krabbe et al. 1991; Davidge et al. 1997b; Blum et al. 2003), while there are other young clusters within the central 100 pc (e.g., Cotera et al. 1996; Figer et al. 1999) and at even larger distances (Launhardt et al. 2002). The structural properties of the region near the Galactic center (Serabyn & Morris 1996), the presence of shells at large \( R_{GC} \) that apparently originate from the inner regions of the Galaxy (Bland-Hawthorn & Cohen 2003), and the analysis of the stellar content near the Galactic center (Blum et al. 2003) together suggest that the current star-forming activity near the Galactic center is not a unique event, but is likely an ongoing or episodic phenomenon with a timescale shorter than a gigayear. Nuclei similar to Sgr A are also common in nearby spiral galaxies, further supporting the argument that nuclear star formation is episodic (e.g., Davidge & Courteau 2002).

The timescale for the disruption of star clusters near the Galactic center is short (e.g., Figer at al. 1999), and individual stars may be scattered out of the disk plane by interactions with giant molecular clouds (Kim & Morris 2001). Consequently, the stars that form along the plane of the disk in the inner regions of a spiral galaxy can diffuse away from their natal locations and be injected into the surrounding bulge. Processes of this nature could explain the presence of a diffuse intermediate-age population in the inner Galactic bulge (Wood & Bessell 1983; Harmon & Gilmore 1988; Lopez-Corredoira et al. 2001; but see also van der Veen & Habing 1990).

The spatial distribution of the C stars seen in bulge 1 and 2 provide clues about their origins. If they formed in a nuclear region, it can be anticipated that they will be concentrated toward smaller radii. Such a trend is not seen in the ALTAIR data, although the uncertainties are high. The very red objects in the Stephens et al. (2003) sample, which were identified as LPVs in that study, are also uniformly distributed. Perhaps the greatest challenge to any model that tries to associate the C stars with the Galactic bulge is the apparent absence of C stars associated with the Galactic bulge. This is a mystery that has been known for some time (e.g., Frogel & Whitford 1987). The geometric center of M31 has a very red \( V - K \) color (Davidge et al. 1997a), which may be due to a population of AGB stars that formed during the past gigayear.

Studies of late-type spiral galaxies indicate that the density of molecular star-forming material is coupled to disk properties, such as the central disk density (Boker et al. 2003), rather than properties of the inner spheroid, and thus it is likely that the C stars in bulge 1 and 2 formed as part of the inner disk of M31 rather than the inner spheroid. Nevertheless, the presence of C stars in the inner regions of M31 suggests that the bulge of this galaxy may be subject to secular processes. Kim & Morris (2001) argue that 1–2 Gyr is required for stars in the inner Galaxy to scatter and form an aspect ratio similar to that of the most luminous AGB stars in the Galactic bulge. This is shorter than the upper age limit of C stars based on statistical studies.
(Cole & Weinberg 2002), so it is possible that C star progenitors may survive long enough to be redistributed throughout the inner bulge. A radial velocity study of the bright, red stars that occur throughout the central few arcminutes of M31 will provide insight into the nature of these objects.

We close by noting that with $R_{GC} = 2'$, bulge 1 does not overlap with the central region that has been the target of population studies based on integrated spectroscopic information. Nevertheless, the spatial distribution of the C stars detected here suggests that they are well mixed throughout the sight line within a few arcminutes of the center of M31, and thus it seems reasonable to expect that some C stars will almost certainly occur at smaller $R_{GC}$ than sampled by bulge 1. If this is the case, the C stars seen here may be the brightest members of the intermediate-age population that has been detected spectroscopically.

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