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GALACTIC BULGE M GIANTS. IV. 0.5–2.5 MICRON SPECTROPHOTOMETRY AND ABUNDANCES FOR STARS IN BAADE'S WINDOW

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ABSTRACT

We have obtained 0.45–2.45 μm spectrophotometry with a resolution $\lambda/\Delta\lambda \sim 1000$ of a representative sample of M giants in Baade's Window and the solar neighborhood. From an analysis of strong atomic lines of Na I and Ca I in the K band, we derive a mean metallicity of the M giants in Baade's Window of $\langle[M/H]\rangle = +0.3$, comparable to that for the K giants. We demonstrate that $J-K$ is a good temperature indicator for both the field and bulge nonvariable M giants, and that the relationship between the two quantities is the same for both types of stars. In addition, there is no difference in the surface gravity between bulge and field giants of the same $J-K$ color (i.e., temperature). From this result we show that the difference in [M/H] between the bulge and field stars based on the first-overtone CO bands is consistent with that derived from the atomic lines. However, when compared with local M giants of the same *spectral class*, bulge M giants are hotter by about 400 K, and have higher gravities by about 0.6 dex.

A major difference in the overall spectral energy distributions of bulge and local M giants is that the classical H-band bump, attributed to the opacity minimum of the H^- ion near 1.6 μm, is considerably reduced in many of the bulge stars. This is consistent with our suggestion in earlier papers that other opacity sources may compete with or even replace H^- as the major opacity source and thus be responsible for the difference in the JHK colors of bulge and field giants. However, the new data do not support the suggestion that H_2O absorption is the main cause. Spectra of many of the bulge giants show an unidentified absorption trough near 1.6 μm whose strength may correlate with the difference between bulge and field giants in $J-H$.

Subject headings: opacities — spectrophotometry — stars: abundances — stars: late-type

1. INTRODUCTION

The M giants of the Galactic bulge provide a unique opportunity for the study of late phases of stellar evolution in old, metal-rich populations. Easily detected in grism surveys (Blanco, McCarthy, & Blanco 1984; Blanco 1986, 1987; Blanco & Terndrup 1989), these stars appear to be photometrically and spectroscopically equivalent to the late-type stars that provide half the bolometric luminosity of E and S0 galaxies (Whitford 1978; Frogel & Whitford 1987, hereafter Paper I; Frogel 1988; Terndrup, Frogel, & Whitford 1990, hereafter Paper III). Establishing their metallicity, therefore, is of importance not only for determining the evolutionary state of the Galactic bulge, but also for the interpretation of the integrated light of other galaxies.

Many properties of the bulge M giants at $|b| < 10°$ indicate a high metallicity for these stars. For example, compared to nearby stars of the same color or spectral type, they have stronger 2.29 μm absorption from CO (Frogel et al. 1990, hereafter Paper II), and stronger TiO absorption in the near-infrared (Paper III). In the $J-H$, $H-K$ plane, these giants extend the sequence of changing colors from globular cluster to solar neighborhood giants (Paper I; Frogel, Persson, & Cohen 1983). The mean metal abundance of the M giants in Baade's Window (BW) has been estimated as $[M/H] \sim +0.2$ from the strengths of CO and TiO (Papers II and III; see also Sharples, Walker, & Cropper 1990), in agreement with that derived for the K giants (Whitford & Rich 1983; Rich 1988), the presumed progenitors of the M stars. This value decreases to ~ -0.2 at $b = -12°$.

Some of the observed properties of the bulge giants, however, cannot be simply explained by enhanced metallicity with respect to local stars. First of all, in C-M diagrams, the mean locations of the bulge giant branches are significantly bluer than would be expected from an extrapolation of the colors of globular cluster giant branches to higher metallicity (Papers I and II; Terndrup 1988). Second, the spread in abundance deduced for the M giants from infrared photometry or spectroscopically from TiO bands (Papers II and III) in any one bulge field is quite small, no larger than that represented by the decline of about 0.4 dex in the mean abundance of the M giants between 0.4 and 1.5 kpc from the Galactic center. In contrast, the K giants in BW have an abundance spread with a FWHM of about a factor of 10 (Rich 1988).

A major difficulty in interpreting the broad-band colors of the bulge M giants, particularly in the infrared where the bulk of their energy is emitted, is insufficient knowledge about the effects of the various molecular absorbers in cool stellar atmospheres. For several reasons, a better understanding of these colors might be gained through spectroscopic observations in

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the infrared. First, the photometric system used for earlier studies of the M giants measures the effects of H_2O and CO in the K band but does not sample the absorption from these molecules at H nor does it measure the absorption from molecules like TiO in the J band. Based on photometry alone, we postulated in Paper I that the H_2O molecule plays a significant role in producing the unique colors of the bulge M giants, and that opacity from H_2O may compete with or even surpass that of the H^- ion as the principal source of continuous opacity in the metal-rich stellar atmospheres. This hypothesis can be tested with infrared spectra of the bulge giants. Furthermore, there have been recent advances in theoretical calculations of the opacity sources in cool atmospheres (Alexander, Augason, & Johnson 1989), and models have been made that include the effects of some of the most abundant molecules on broad-band colors (Bessell et al. 1989). Future tests of these models can be made with accurate spectrophometry of late-type stars like those in the bulge. Finally, it would be valuable to obtain metallicity estimates for the bulge M giants from atomic lines to provide a better comparison with the metallicity distribution derived for bulge K giants.

In this paper we present spectrophotometric observations of bulge and local M giants from 0.45 to 2.5 μm at a resolution of ~ 1000. This is the first time that such comprehensive spectral coverage at this resolution has been published for cool stars. From these new data we are able to derive metallicities for the bulge M giants based on the strengths of atomic lines from Na I and Ca I in the K band. We are also able to examine the effects of molecular absorption on the infrared energy distributions and to see if such absorption can account for the color differences in JHK observed between bulge and local giants (Papers I and II). Some of these results were presented in preliminary form by Whitford, Terndrup, & Frogel (1990).

2. OBSERVATIONS AND DATA REDUCTION

The CTIO Infrared Spectrometer (IRS) was used on the 4 m telescope during the 1986–1988 observing seasons to obtain spectra of 18 M giants in the solar neighborhood and of 14 M giants in the BW field of the Galactic bulge ($l = 1.0°$, $b = -3.9°$). Spectra in the optical and near-infrared were obtained for many of the same stars during the 1984–1988 observing seasons with the RC spectrograph and a CCD detector on the CTIO 4 m telescope. These or similar data have been described at length in Paper III. The wavelength limits of the intervals scanned at each grating setting of the two spectrographs together with the resolutions of the optical and infrared spectra in our sample are listed in Table 1.

TABLE 1
SPECTRAL REGIONS OBSERVED

Region	Wavelength Range (μm)	Resolution ($\lambda/\Delta\lambda$)	Resolution (Å)	Notes
B	0.45–0.78	1070	5.8	
R	0.69–1.03	1500	5.8	
R'	0.77–0.90	3580	2.8	
I	0.99–1.05	970	10.6	
I'	0.89–1.11	970	10.6	1
J	1.12–1.37	880	14.2	
H	1.49–1.81	1140	14.6	2
K	1.99–2.43	1060	20.9	

NOTES.—(1) Contaminated by order overlap for $\lambda < 0.94$ μm. (2) Poor signal-to-noise ratio for $\lambda > 1.75$ μm.

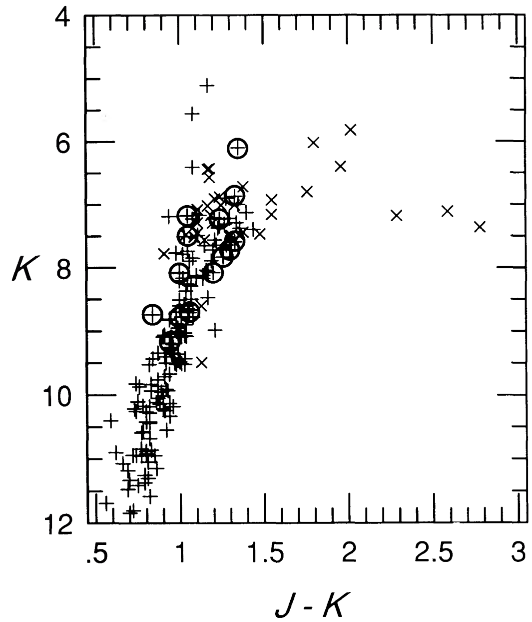

FIG. 1.—A dereddened C-M diagram for M giants in Baade's Window with photometry from Paper I. The open circles are the stars observed with the infrared spectrometer for this paper. Other M giants are plotted as plus signs and crosses; the latter are the long-period variables.

The stars we observed are listed in Table 2. The BW stars with prefixes 4- and 4-B are cataloged by Blanco et al. (1984) and by Blanco (1986), respectively. The HD stars were selected from Houk's (1978, 1982) and Houk & Cowley's (1975) compilations. The second column of Table 2 lists the spectral types from Houk or Blanco; the latter are uncorrected for the small differences in their classification schemes (Paper III). The third and fourth columns summarize the wavelength intervals scanned in the optical and infrared (Table 1). The BW and solar neighborhood samples were chosen to encompass the largest possible spread in temperature given limits on telescope time; the bulge sample therefore does not represent an unbiased measure of the population. The BW sample, though, is more or less evenly distributed over spectral classes M5–M9; it is over these classes that the bulge and local stars show their greatest differences in photometric and spectroscopic properties (Papers I and III, and discussion below).

During the observations, a deliberate attempt was made to sample bulge stars throughout the range of magnitudes present at each spectral type. Known LPVs were excluded. Figure 1 compares the distribution in a K, $J-K$ C-M diagram[4] of the stars for which spectra have been obtained with that for the full sample of BW giants from Paper I. In Figure 1, LPVs are plotted as X's and the non–LPVs as plus signs. The stars in our spectrophotometric sample are displayed as open circles; here the photometry is also from Paper I except for a few stars not tabulated there, where the photometry is from this study as described below. Only two of the sample, 4-B066 and 4-289, are brighter or bluer than the bulk of the stars in Figure 1; these two stars may therefore may be located on the extreme

[4] The magnitudes and colors of the bulge M giants in this paper were corrected for reddening according to the precepts in Paper I. No correction was applied to the photometry of the bright and presumedly unreddened field giants.

TABLE 2

LOG OF OBSERVATIONS AND IRS PHOTOMETRY

				IRS			Paper I			IRS – Paper I			
Star (1)	M (2)	IRS (3)	CCD (4)	*K* (5)	*J*-*K* (6)	*H*-*K* (7)	*K* (8)	*J*-*K* (9)	*H*-*K* (10)	*K* (11)	*J*-*K* (12)	*H*-*K* (13)	Notes (14)
4-028	7	*JHK*	*BR*	7.37	1.37	0.45	7.23	1.24	0.39	+0.14	+0.13	+0.06	
4-055	8	*IJHK*	*BR*	7.76	1.29	0.40	7.72	1.30	0.41	+0.04	-0.01	-0.01	
4-078	5	*JHK*	*BR*	7.50	1.05	0.21	...	...	...	...	...	...	
4-093	6	*JHK*		7.18	1.03	0.22	7.18	1.05	0.25	0.00	+0.02	-0.03	
4-107	6	*JHK*	*BR*	8.80	1.00	0.26	8.78	1.00	0.26	+0.02	0.00	0.00	
4-133	6	*IJHK*	*BR*	8.64	1.02	0.24	8.70	1.06	0.25	-0.06	-0.04	-0.01	
4-165	7	*JHK*	*BR*	8.23	1.19	0.32	8.08	1.20	0.35	+0.15	0.01	-0.03	
4-179	7	*IJHK*	*BR*	6.70	1.28	0.34	6.86	1.33	0.41	-0.16	-0.05	-0.07	
4-205	8	*I′JHK*	*BR*	7.58	1.38	0.44	7.58	1.33	0.38	...	+0.05	+0.06	1
4-247	8	*JHK*	*BR*	7.83	1.20	0.33	7.83	1.26	0.37	0.00	-0.06	-0.04	
4-289	9	*IJHK*	*BR*	6.03	1.28	0.43	6.11	1.35	0.44	-0.08	-0.07	-0.01	
4-B047	5	*JHK*		8.14	0.94	0.18	8.09	1.00	0.24	+0.05	-0.06	-0.06	
4-B064	3	*JHK*		9.17	0.94	0.19	...	...	...	...	...	...	
4-B066	3	*I′JHK*	*BR*	8.79	0.84	0.14	8.74	0.84	0.16	+0.05	0.00	-0.02	
HD89060	4	*I′JHK*	*BR*	2.16	1.18	0.30	...	...	...	...	...	...	
HD89951	3	*I′JHK*	*BR*	3.92	1.13	0.20	3.92	1.10	0.23	0.00	+0.03	-0.03	
HD94152	6	*I′JHK*	*BR*	0.82	1.20	0.30	...	...	...	...	...	...	
HD99495	4	*I′JHK*	*BR*	2.02	1.14	0.25	...	...	...	...	...	...	
HD100569	2	*I′JHK*		3.65	1.01	0.22	...	...	...	...	...	...	
HD100783	2	*I′JHK*		4.12	0.99	0.21	4.13	0.99	0.19	-0.01	0.00	+0.02	
HD102608	7	*I′JHK*	*BR*	-1.26	1.29	0.41	...	...	...	...	...	...	
HD102766	6	*I′JHK*		1.14	1.30	0.38	...	...	...	...	...	...	2
HD104745	3	*I′JHK*		2.79	1.13	0.28	...	...	...	...	...	...	
HD108849	7	*I′JHK*	*R′*	-1.00	1.19	0.39	-0.91	1.22	0.33	...	...	...	3, 4, 5
HD109225	5	*I′JHK*	*BR*	2.00	1.18	0.27	...	...	...	...	...	...	3
HD109467	6	*I′JHK*	*BR*	2.95	1.18	0.26	...	...	...	...	...	...	3
HD113285	8	*IJHK*	*R′*	-1.09	1.34	0.43	-1.18	1.26	0.36	...	...	...	4,6
HD114691	7	*IJHK*	*R*	-1.93	1.24	0.33	-1.88	1.25	0.34	...	...	...	4,7
HD126903	6	*I′JHK*	*BR*	0.80	1.15	0.26	...	...	...	...	...	...	3
HD163783	7	*IJHK*	*R*	...	1.12	0.26	...	...	...	...	...	...	8
HD173604	4	*I′JHK*	*R*	...	1.04	0.23	...	...	...	...	...	...	8
HD183847	7	*IJHK*	*R*	...	1.24	0.33	...	...	...	...	...	...	8

NOTES.—(1) Not observed in *K* with monitor channel. Photometry from FW87 used for fluxing *K* spectrum. (2) Misclassified by Houk 1982 as type M3; typed as M6 here from TiO strength (Paper III). (3) Some or all infrared scans done twice. (4) Photometry from Frogel et al. 1978. (5) = BK Vir. (6) = RT Vir. (7) = SW Vir. (8) See Table 1 for wavelength limits and resolution of infrared scans and optical spectra. Not photometric when observed; assumed colors from mean of local stars of same spectral class.

near side of the bulge or in the disk along the line of sight to BW.

The entrance aperture of the IRS for the observations was 4 × 4 mm, corresponding to 7″ × 7″ at the f/30 Cassegrain focus of the CTIO 4 m telescope. Order separation was done by broad-band filters identical to those used for *JHK* photometry of bulge stars (Papers I and II), plus two filters that we have called *I* and *I′* centered near 1 μm. The detector array consisted of eight Cincinnati Electronics InSb detectors of size 0.25 by 0.8 mm on 0.275 mm centers. Two gratings were used with spectral resolutions of about 1000 per detector element. Complete coverage through the order separating filters was accomplished by stepping the gratings by an amount equal to 8 times the detector spacing. Two methods were used for sky subtraction. In the first method, two star-sky pairs were observed for each position of the grating, and the resulting eight channel portions of the spectrum were averaged by the data-taking software before the grating was moved to the next wavelength position. In the second method, which was considerably faster, a complete scan was made chopping to a single sky area; the scan was then repeated with another sky area on the other side of the program star and the two resulting scans averaged. No difference in the two techniques was detected.

Wavelength calibration of the spectra was achieved by centering narrow emission lines from lamp spectra on designated pixels, thereby calibrating the relation between grating position and wavelength. As the scans through the spectra were obtained, the wavelengths of the individual pixels were calculated from the known grating position and detector geometry. The wavelength calibration was performed only a few times per night, however, resulting in errors of up to 1.5 pixels in the wavelength calibration of the IRS scans; this error does not effect any of our analysis, appearing only on the wavelength scale for plots of the spectra.

Table 1 lists the order separating filters used for the observations. The scans were almost always made well into the wings of the filters and/or the atmospheric absorption bands near *H* and *K*; the resulting low signal-to-noise ratio portions of the scans were usually deleted in the resulting spectra. The *JHK* filters remained the same throughout the observations. In 1986 we used a narrow-band filter at *I* with half-power points at 0.99 and 1.05 μm. In the last two seasons, we switched to a wider filter, designated *I′*, which had high throughput from 0.85 to 1.11 μm. The portion of the *I′* scans below 0.94 μm, however, were significantly contaminated by light from other spectral orders, and is therefore not shown. The *I′* and *J* filter transmissions did not overlap in wavelength, even though there is no atmospheric absorption band between them. Consequently, the coverage between 0.94 and 1.35 μm is incomplete. The entrance aperture projected onto approximately 1 pixel in all filters.

Approximately 10% of the light passing through the entrance aperture was picked off by a beam splitter and sent to a second, identical, set of *JHK* filters to be measured by one 0.5 mm InSb detector. The raw spectral scans were divided by the output of this monitor channel to eliminate the effects of variation in the signal from poor seeing, guiding errors, and clouds. This process reduces such effects to less than 1% of the level of the spectrum, except for the very faintest bulge stars, in which the error is about 3%. The process of division by the monitor channel output and the assembly of the individual eight channel spectra into the full scans through each filter was done simultaneously in real time by the data-taking software. After correction with monitor channel data, the scans were divided by scans of a continuum lamp to eliminate the effects of sensitivity variations among the eight detectors. The spectra were placed on a linear wavelength scale by solving for the (nearly linear) relation betweem tabulated wavelength of each element of the scans; the difference between the linear fit and the tabulated wavelengths was everywhere less than 0.1 pixel.

Atmospheric absorption corrections to the spectra were determined from observations of the same early-type stars used as standards (Table 3 and below) and required two steps. On each night scans were made of one or two standards to span the range of air mass through which the program stars were observed. These standard star scans were flattened by division by a third-order spline fit to the continuum points. Over each of the stellar absorption lines, the flattened scans were replaced by unity; there remained the absorption features caused by the atmosphere. This process was not well determined at the few percent level in *J* and *H* where the atmospheric features overlapped somewhat with the hydrogen lines in the stellar spectra. The scans of the bulge and local M giants were then divided by the processed scans of the standards, for first-order elimination of atmospheric features. This correction was appropriate for about $\frac{2}{3}$ of the program stars—those observed at air masses near those of the standards. In the second step, the scans of two flux standards taken at different air masses were divided and highly smoothed. From the resulting ratio, interpolation functions were constructed which corrected for the differential effects of the terrestrial atmosphere over large wavelength ranges or over strong terrestrial features between the air mass of the M giant scan and that of the flux standard. This second step eliminated remaining atmospheric effects at the 2% level, except in the cores of the strong CO_2 doublets near 2.01 and 2.06 μm and at the extreme red end of the *H* scan where errors can be as large as 20%. None of the discussion throughout this paper depends on the details of the atmospheric corrections.

Data recorded from the monitor channel were later reduced with standard reduction programs to derive broad band magnitudes and colors for the stars with respect to the photometric standards in Table 3. Table 2 presents these data. The fifth through seventh columns list, respectively, the values of *K*, $J-K$, and $H-K$ for the stars in Table 2. For stars observed twice the values are averages. No *K* values are give for HD 163783, HD 173604, and HD 183847 as they were not observed on photometric nights; the colors of these three stars are assumed to be like those of field M giants of the same spectral class. The eighth through tenth columns of Table 2 give the magnitude and colors from conventional photometry (Paper I, and from Frogel et al. 1978 for a few stars), while the eleventh through thirteenth columns are the differences between the two sets of values in the sense IRS minus Paper I. These differences are illustrated in Figure 2. The mean differences and standard deviations for all stars are $\Delta(K) = 0.014 \pm 0.076$, $\Delta(J-K) = -0.009 \pm 0.053$, and $\Delta(H-K) = -0.014 \pm 0.036$. The scatter about the mean is somewhat larger—particularly in *K*—than typical errors of measurement from Paper I (± 0.03 in *K*, and ± 0.02 in $J-K$ or $H-K$). This is probably because many of the late M giants in the bulge are small amplitude variables. Redder stars would be expected to exhibit larger variations. Figure 2 shows this to be the case. In the discussion of this paper, the IRS values for the broad-band colors will be used when available.

The infrared spectral scans were converted to an absolute λF_λ scale based on the flux calibration in Table 4, the second

TABLE 3

MAGNITUDES OF PHOTOMETRIC STANDARDS

Star	Class	*I*, *I′*	*J*	*H*	*K*	Notes
BS 4167.........	F4 IV	3.42	3.25	3.13	3.10	1, 2
BS 4689.........	A2 V	3.79	3.79	3.78	3.77	1, 3
BS 8576.........	A0 V	4.27	4.27	4.27	4.26	4

NOTES.—(1) *JHK* from Elias et al. 1982. (2) *I* and *I′* magnitudes from interpolation between *J*, $R-J$, and $I-J$ values from Johnson et al. 1966. (3) *I* from assumed $I-J = 0.00$. (4) Derived from photometry from IRS monitor channel with respect to BS 4167.

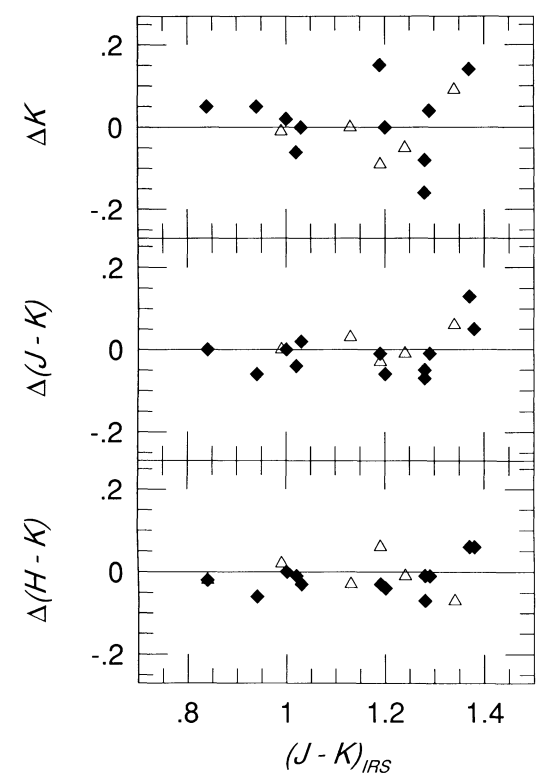

FIG. 2.—Differences between photometry carried out with the IRS and results reported in Paper I and Frogel et al. (1978), in the sense IRS − other, as a function of $J-K$ measured with the IRS. Open symbols are HD stars, and filled symbols are BW stars.

TABLE 4

ADOPTED FLUX SCALE

Filter	λ (μm)	F_ν (Jy)	Notes
I, I'	1.02	2115	1, 2
J	1.25	1570	3
H	1.65	1050	3
K	2.20	664	3
L	3.50	266	3

NOTES.—(1) Hayes 1979. (2) Kurucz 1979, matched to Hayes 1979 at $\lambda = 5500$ Å. (3) Campins, Rieke, & Lebofsky 1985, adjusted to mag(Vega) = 0.0.

and third columns of which show the central wavelength of each spectral region and the adopted monochromatic flux of a zero-magnitude star, respectively. The scans were multiplicatively scaled so that the monochromatic magnitude at the central wavelengths of each scan were equal to the broad-band magnitudes derived from the monitor channel photometry in Table 2. The scaling at this step used the observed magnitudes, uncorrected for reddening, for the bulge and local stars, thus producing the observed spectral energy distribution (SED). This scaling process was chosen for simplicity over a formally correct solution, in which the spectra would be scaled so that the convolution of a scan with the appropriate filter function matched the broad band magnitude. Any systematic errors in the relative fluxing between the infrared scans applies to all stars in the sample, and so would have no effect on analysis of differences in the SEDs of the various stars.

The full details of the reduction of the optical spectra may be found in Paper III. Two grating settings at low resolution were used to cover 4450–10425 Å (the fourth column of Table 1). The optical spectra were placed on a relative F_λ scale by observations of spectrophotometric standards from Stone & Baldwin (1983). The point-to-point accuracy of the calibration as gauged by the rms scatter about the mean flux curve of the individual standards was 3%–5%. Because of undetermined slit-edge losses and frequent nonphotometric weather, the absolute fluxes of the stars are unknown. The various segments of the spectra where scaled to match the flux in the I or I' scans from the IRS or, where there was no actual overlap in wavelength coverage, by reasonable interpolations in spectral type between stars with better determined SEDs.

In the final step of the processing, the bulge SEDs were corrected for interstellar extinction using a spline function in wavelength which was fit to the values of A_λ (λ from B through L) adopted in Paper I.

3. SPECTRAL ENERGY DISTRIBUTIONS

Figures 3–5 present the spectral energy distributions from 0.5 to 2.5 μm of selected bulge and local M giants from the list in Table 2. These have been smoothed by 2 pixel averaging from the original spectral scans and have been normalized via division by a 3300 K blackbody spectrum. For convenience, the names of the stars, their $J-K$ colors, M types, and their TiO and CO strengths are indicated at the bottom of each panel [the TiO strengths are measured by the S(7890) index of Paper III]. Note that Figures 3–5 have different vertical scales, and that the wavelength scale in each plot is linear for $\lambda < 1.0$ μm and logarithmic for $\lambda > 1.0$ μm.

On Figure 3 are marked the well-known absorption features in M giants. Shortward of 1 μm the spectra are dominated by TiO absorption, with VO appearing in the latest stars. (Note that the atmospheric A and B bands and various weaker telluric features have not been removed from the spectra in the interval $\lambda < 1$ μm.) In the very latest stars, the weak ϕ bands of TiO begin to appear near 1.29 μm. At all M types the strong CO absorption in the H and K bands is clearly present; in the K band the absorption from CO gradually increases in strength with declining temperature. Later than about M6 the H and K bands are affected by absorption from H_2O. Our spectra unfortunately do not sample the red system of CN at 1.1 μm.

Figure 3 illustrates the most obvious difference between the SEDs of the bulge and local M giants which has been discussed in our previous papers, namely that bulge stars are of considerably later spectral type than local giants of similar infrared colors. The top two SEDs in the figure are for two local giants with $J-K \sim 1.0$, while the next two are for bulge stars of similar color. Though all four of these stars have nearly identical $J-K$, the bulge SEDs are considerably reduced below 1 μm because of stronger absorption from TiO and VO; this strong absorption leads to a later spectral class for the bulge stars at a given infrared color. The bottom spectrum is for a field giant with TiO absorption just slightly stronger than the two bulge stars; compared to the latter the field giant has a significantly redder $J-K$ and is cool enough that the steam band between H and K is starting to appear.

The SEDs in Figure 3 and 4 also illustrate the difference in JHK colors between bulge and field giants, in that the former typically have bluer $J-H$ and redder $H-K$ colors at a given $J-K$ (cf. Fig. 2 of Paper I). The cause of this seems to be a variation in the level and shape of the H spectrum. The two bulge spectra in Figure 3 were selected to display the extreme ranges of this effect; in that figure the bulge stars 4-078 and 4-107 have very similar overall SEDs, except that the flux at H is considerably reduced in the latter star. The SEDs of these two stars are repeated in Figure 4, along with two others of similar $J-K$ color. In Figure 4, these four stars are plotted in order of decreasing $J-H$ and increasing $H-K$. The first star in the sequence, 4-078, has $J-H$, $H-K$ colors close to the mean colors for solar neighborhood stars of similar $J-K$ color as would be inferred from Figure 3 (cf. Frogel et al. 1978). As the sequence continues through 4-093, 4-133, and 4-107, the mean level of the H spectrum declines, and there is a local minimum in the SED appearing near 1.6 μm.

In Figure 5 we present SEDs for some of the coolest stars in our sample. These stars all have $J-K$ near 1.30; in the figure they are arranged in order of decreasing $J-H$. Here the effects of H_2O absorption on the H and K bands is appreciable, and there is strong absorption at J from TiO. Two of the stars, 4-055 and 4-289, exhibit the local minimum in the H band seen in the spectra of Figure 4.

From the SEDs presented in Figures 3–5, it is apparent that in the latest M giants the steam bands have a large influence on the emitted flux at H and K. But even at warmer temperatures, there can be considerable variation in the level and curvature of the H spectrum. This seems to be the cause of the color differences (bluer $J-H$, redder $H-K$) of the bulge M giants with respect to their local counterparts. In the next two sections, we explore the details of the SEDs of the bulge M giants to derive metallicity estimates and to discuss the effects of CO and H_2O absorption on the JHK colors.

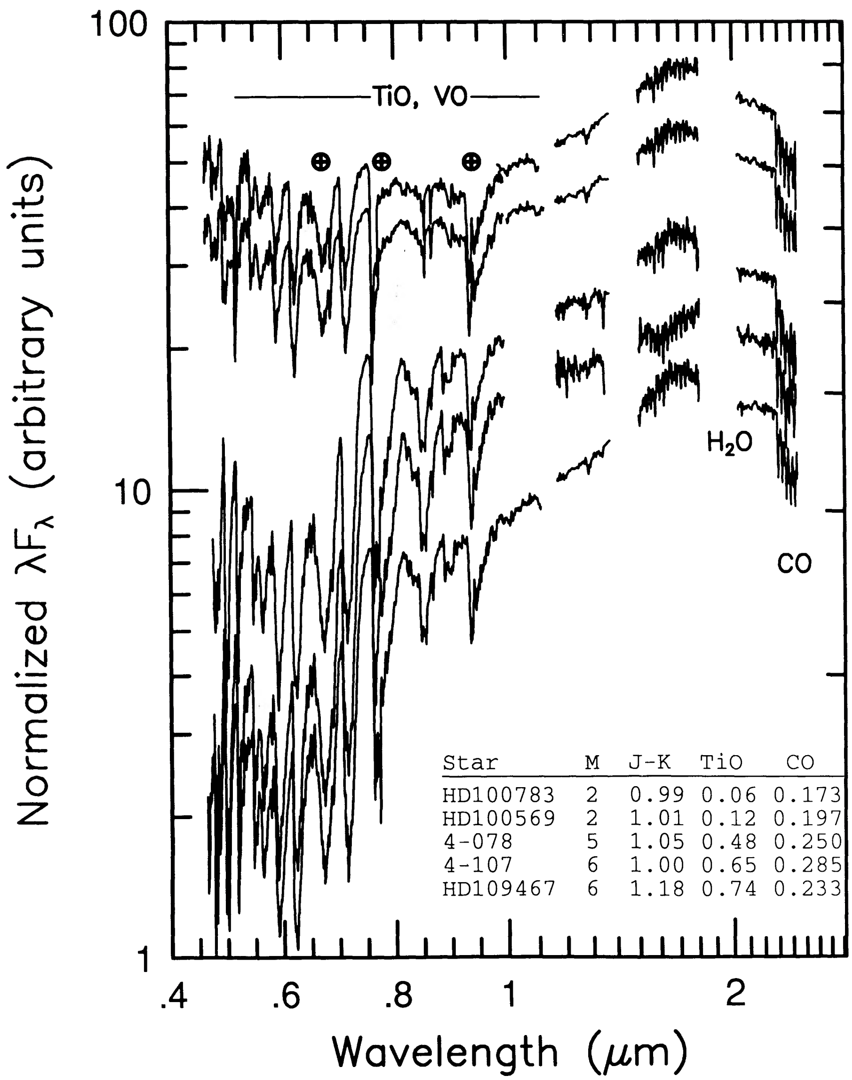

FIG. 3.—A comparison of the spectral energy distributions (SEDs) of bulge and local stars near $J-K = 1.0$. These spectra have been smoothed from the original scans and normalized via division by a 3300 K blackbody curve. The bulge SEDs have been corrected for interstellar extinction. The wavelength scale is linear for $\lambda < 1.0$ μm and logarithmic for $\lambda > 1.0$ μm. Prominent telluric and stellar absorption features are marked.

4. ABUNDANCES OF M GIANTS IN BAADE'S WINDOW

In Papers I and III we estimated metallicities for M giants in Baade's Window from the strength of CO bands at 2.3 μm and TiO bands in the near-infrared, and from the relative positions of the stars in the $J-H$, $H-K$ plane. All three of these estimates yielded the same result, that the mean metallicity of M giants in Baade's Window is about twice solar, consistent with that for the K giants (Whitford & Rich 1983; Rich 1988). In this section and the next we derive new abundance estimates for the M giants in BW based on strong atomic lines in the 2.2 μm spectral region. These lines should yield more accurate abundances than those based on molecular bands or colors, which are influenced by the gravity in the stellar atmospheres. We will also determine from our spectra new measures of the strength of CO and H_2O absorption, compare them to the values derived from filter photometry, and discuss the effects of gravity on the earlier metallicity estimates from CO.

4.1. *Temperature Estimates for Bulge M Giants*

First we need to consider the question of the temperatures of the M giants in Baade's Window. Ridgway et al. (1980) derived effective temperatures for late-type stars from diameters measured by lunar occultations and calibrated these temperatures against both $V-K$ and $104 - L$ (104 is the 1.04 μm continuum filter in the Wing [1971] eight-color system). They note, though, that for mid- to late-M giants, temperatures based on their $V-K$ scale may be sensitive to variations in TiO strength with metallicity or other atmospheric parameters (cf. Mould & McElroy 1978). That such an effect is operating in the bulge giants in obvious from the SEDs presented in Figure 3, since the bulge giants have considerably stronger TiO and consequently redder $V-K$ colors at a given $J-K$. Recent model atmosphere calculations by Bessell et al. (1989) also show that the relation between $V-K$ and temperature depends strongly on metal abundance, but that the relation between the $104 - L$

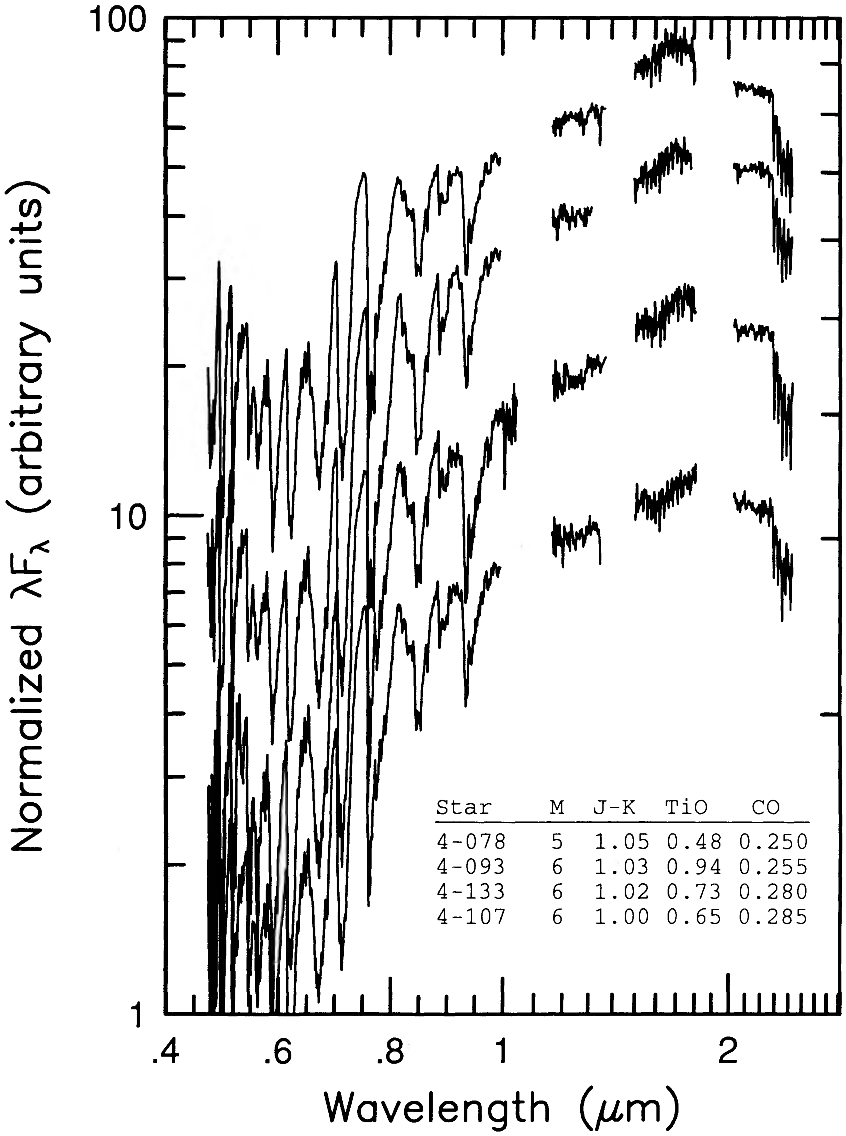

FIG. 4.—SEDs for four bulge M giants having $J-K$ near 1.02, arranged in order of decreasing $J-H$ and increasing $H-K$ as described in the text; otherwise, as Fig. 3.

color and effective temperature is virtually independent of metallicity.

In Paper I we presented narrow-band photometry of Baade's Window and field giants using a filter at 1.02 μm from which a [102] $-$ L color can be constructed. As discussed in Paper I, this color should be relatively blanketing free and as useful as the [104] $-$ L color as an estimator of effective temperature for M stars. In Figure 6 we reexamine data from Table 6 of Paper I using [102] $-$ L colors, which were computed by $[102] - L = ([102] - K) + (K-L)$. For the field giants without $K-L$ colors in Paper I, [102] $-$ L was computed from the [102] $-$ C370 index via a linear transformation determined from stars with both colors. The data for the bulge and field giants in Figure 6 are plotted as filled and open points, respectively.

The lowest panel of Figure 6 displays the correlation between spectral class and [102] $-$ L color. As has been found before, the bulge M giants are bluer than local stars of the same M type. The difference between the bulge and local sequences is $\Delta(102 - L) \sim 0.3$ for all spectral classes, which corresponds to a difference in effective temperature of $\sim$400 K (Ridgway et al. 1980), the bulge giants being hotter.

The broad-band colors $V-K$ and $J-K$ are compared to [102] $-$ L in the center and top panels of Figure 6, respectively. As expected from our spectrophotometry and the Bessell et al. (1989) model atmospheres, the bulge giants are somewhat redder in $V-K$ at a given [102] $-$ L than the local stars. (Unfortunately, we do not have $V-K$ colors for the latest field giants, so this conclusion strictly applies only to stars earlier than type M6). In $J-K$, however, the bulge and field stars lie on nearly identical sequences with respect to [102] $-$ L. From this we conclude that both bulge and local giants with the same $J-K$ color have nearly identical effective temperatures.

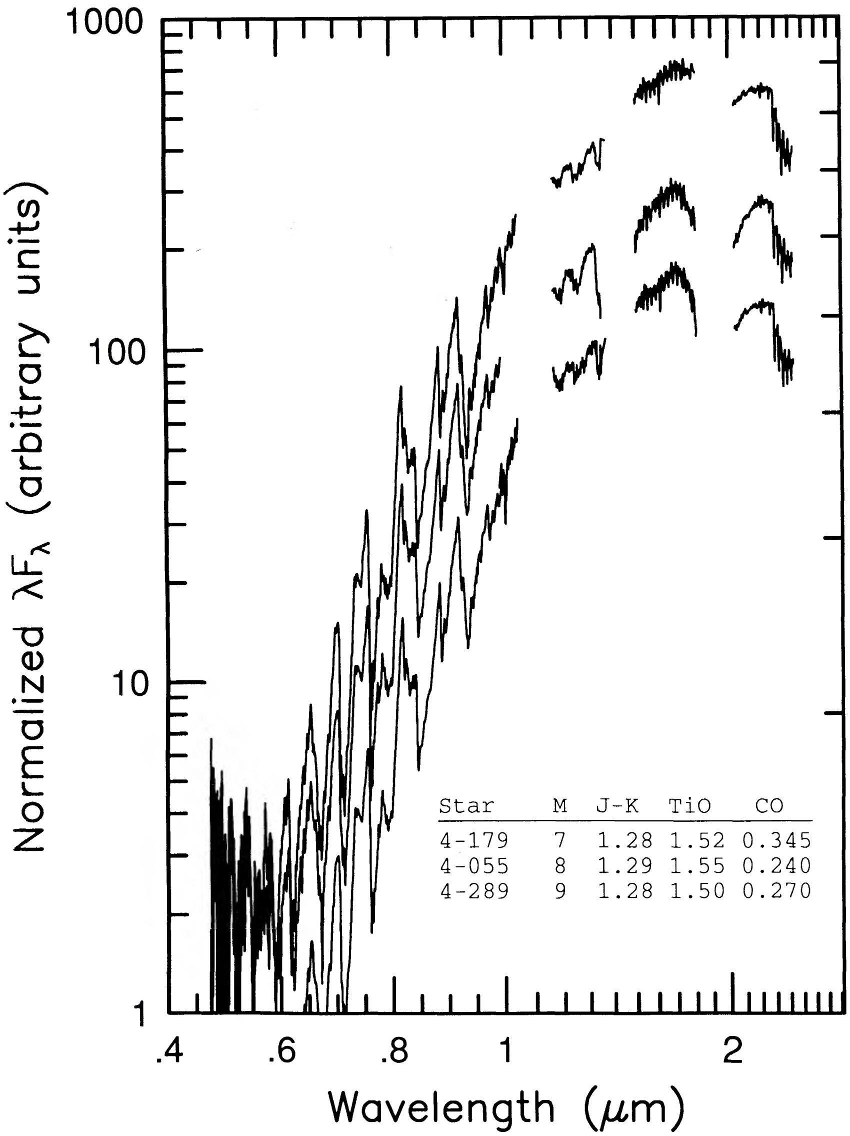

FIG. 5.—SEDs of three late M giants in the bulge. Note the change in the vertical scale from Figs. 3 and 4.

4.2. *Abundances from Atomic Features*

Figure 7 displays the K band spectra of a bulge and a nearby M giant, where the wavelength resolution is that of the original scans. The two strongest atomic features are the Na I doublet at 2.207 μm and Ca I triplet at 2.263 μm (cf. Kleinmann & Hall 1986), which are unresolved at the resolution of our spectral scans. The equivalent widths of these features are assembled in the second and third columns of Table 5, and the average of the Ca I and Na I equivalent widths are plotted against $J-K$ in the top panel of Figure 8. The error bar represents typical uncertainties of a single measurement, ± 0.03 in $J-K$ and about ± 0.5 Å in equivalent width; the error in the average of the equivalent widths will be smaller. The bottom panel of Figure 8 displays the correlation between the two equivalent widths. The Ca I and Na I equivalent widths are correlated, as expected if both are measures of the same physical quantity; the scatter in the correlation is comparable to that expected from the measuring errors alone.

In the mean, the equivalent widths of the two atomic lines in the BW giants are larger than in the local giants by a factor of roughly 1.4. As demonstrated in the previous section, bulge and field giants of the same $J-K$ have nearly the same temperature. According to Deutsch's (1966) rules, the widths of strong lines such as those of Na I and Ca I that are under consideration here (namely from the neutral state of primarily once-ionized atoms) vary as the square root of the abundance with no gravity dependence, assuming non-LTE effects are unimportant. If the mean abundance for the local giants is solar, the mean abundances of the BW giants is [M/H] = +0.3, consistent with the results from CO and TiO in Papers II and III and with the mean value for K giants (Whitford & Rich 1983; Rich 1988). Sellgren et al. (1987) have detected a similar enhancement of the Na I and Ca I strengths of M giants near the Galactic nucleus.

As with previous analyses of the infrared colors and CO strengths, there does not appear to be a wide range of abun-

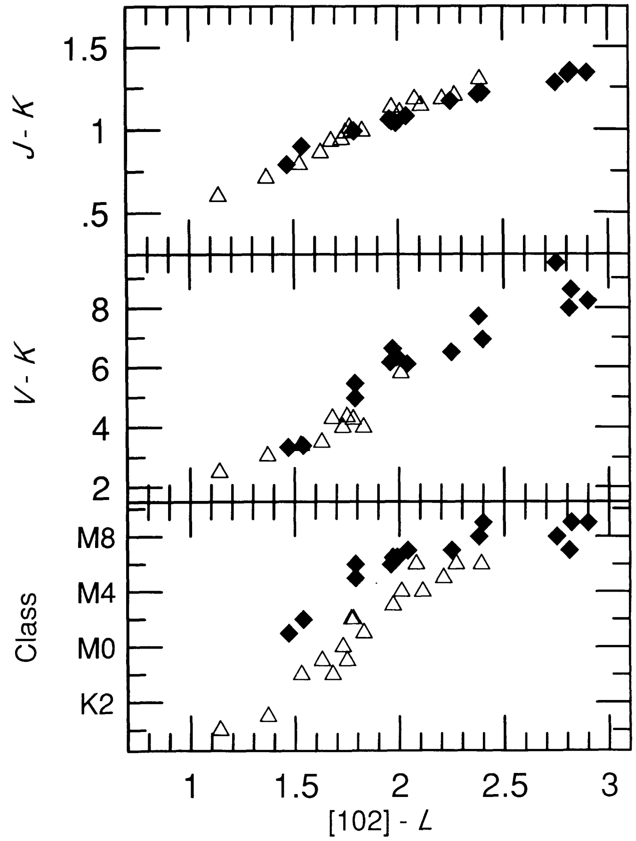

FIG. 6.—The [102] $-$ L colors of bulge and local M giants. Bulge stars are shown as filled symbols; local giants, as open symbols. *Top panel:* $J-K$; *center panel:* $V-K$; *bottom panel:* spectral class.

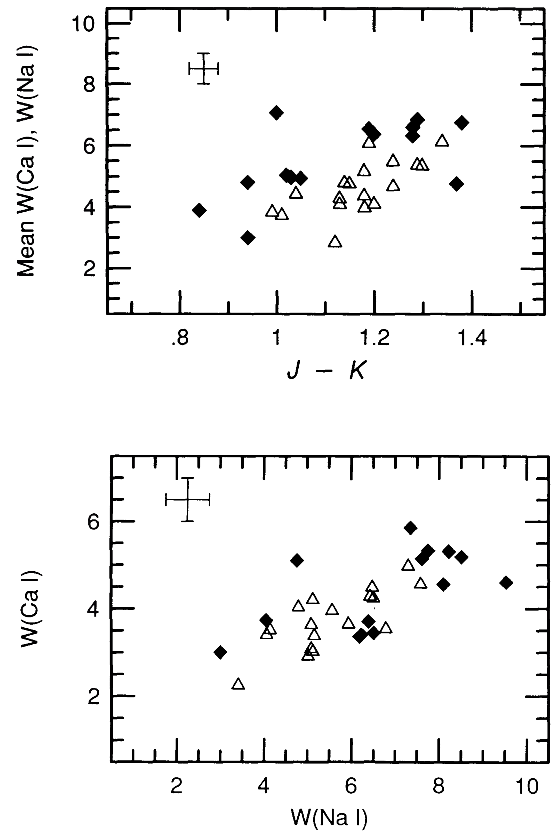

FIG. 8.—Equivalent widths of the Ca I and Na I features in the K band. Units are angstroms. Symbols are as in Fig. 6. *Top panel:* Mean of Ca I and Na I widths against $J-K$; *bottom panel:* correlation of Na I and Ca I widths.

dances present in the bulge M stars based on the atomic line data in Figure 8. With the possible exception of the most outlying points, the scatter in equivalent widths in Figure 8 for either the bulge or the local giants is not much larger than could be accounted for by uncertainties in the measurements. If the FWHM of the bulge M giants' metallicity were as large as ~1 dex measured for the K giants (Rich 1988; Geisler & Friel 1990), the dispersion in equivalent width in Figure 8 should be significantly larger than the separation between the bulge and local star sequences, which is obviously not the case. These new, independent results, therefore, do not remove the discrepancy between the metallicity dispersions of the K and M giants in BW found in earlier papers.

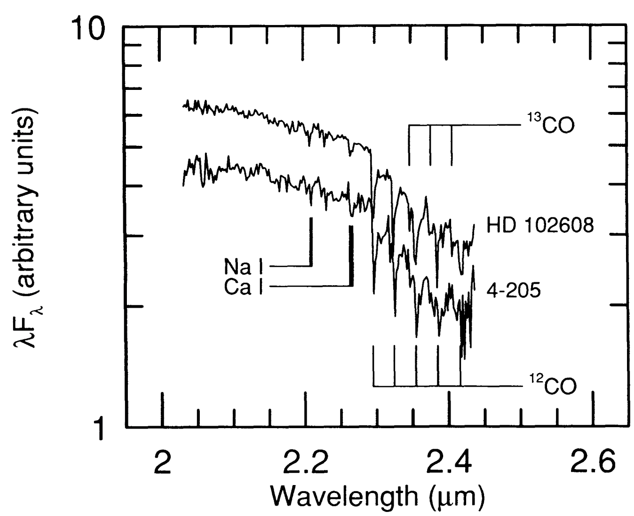

FIG. 7.—Detail of K-band spectrum of a bulge and local M giant. The bulge spectrum has been corrected for reddening. The locations of the absorption features of CO, Na I, and Ca I are marked.

4.3. *Abundances from* CO *Bands: The Effect of Surface Gravity Differences*

Papers I and II contain an extensive discussion of CO absorption in the K band of bulge and field giants as measured by filter photometry, where it was found that bulge M giants extend the observed sequence of increasing CO absorption at a given $J-K$ from globular clusters through metal-rich open clusters. From these data we estimated the mean metallicity of the M giants in Baade's Window to be [Fe/H] = +0.2. With the new spectrophotometric data, we can obtain a more accurate estimate of the strength of the CO absorption band free of effects of continuum slope and overlying H_2O absorption, and reevaluate the earlier metallicity estimates.

We define a spectroscopic K-band index, called CO_K, which is the ratio in magnitudes between the total counts in the observed spectrum and a modified spectrum in which the observed flux in the interval 2.289–2.414 μm is replaced by an extension of the continuum from the interval 2.09–2.26 μm for the warmer M giants, or by an extension of the $H-K$ level for the cooler giants. CO_K, then, measures the amount of flux in magnitudes that the CO bands remove from the SED. We also

TABLE 5

PARAMETERS DERIVED FROM PHOTOMETRY AND SPECTROPHOTOMETRY

Star	W(Ca) (Å)	W(Na) (Å)	CO_K	CO_t	CO_H	H_2O	$(slope)_H$	$(H_2O)_H$	$(curv)_H$
4-028	3.36	6.18	0.088	0.329	0.066	0.32	0.34	0.21	0.14
4-055	5.18	8.51	0.092	0.354	0.058	0.44	0.38	0.30	0.27
4-078	5.10	4.77	0.070	...	0.052	0.14	0.20	0.07	0.03
4-093	3.44	6.50	0.085	0.325	0.052	0.08	0.26	0.05	0.02
4-107	4.60	9.53	0.075	0.360	0.050	0.07	0.09	-0.02	-0.02
4-133	3.70	6.38	0.089	0.329	0.076	0.09	0.15	0.04	0.03
4-165	5.32	7.75	0.085	0.347	0.053	0.14	0.33	0.09	0.06
4-179	4.55	8.10	0.102	0.461	0.046	0.38	0.25	0.11	0.06
4-205	5.30	8.22	0.087	0.345	0.051	0.35	0.43	0.19	0.18
4-247	5.13	7.61	0.085	0.452	0.055	0.35	0.39	0.18	0.08
4-289	5.84	7.35	0.113	0.545	0.093	0.44	0.32	0.27	0.15
4-B047	3.40	6.22	0.071	0.324	0.055	0.06	0.21	0.03	0.02
4-B064	3.00	3.00	0.050	...	0.044	0.05	0.15	0.02	0.02
4-B066	3.73	4.05	0.047	0.251	0.061	0.05	0.13	0.00	0.00
HD89060	3.53	6.78	0.065	...	0.051	...	0.09	0.10	0.05
HD89951	3.38	5.16	0.059	0.280	0.052	...	0.25	0.12	0.07
HD94152	3.08	5.09	0.072	...	0.059	...	0.28	0.20	0.14
HD99495	3.64	5.93	0.071	...	0.033	...	0.19	0.16	0.12
HD100569	3.40	4.06	0.057	0.260	0.052	...	0.18	0.09	0.06
HD100783	3.51	4.14	0.050	0.260	0.040	0.05	0.18	0.05	0.03
HD102608	4.23	6.50	0.085	...	0.056	...	0.23	0.25	0.14
HD102766	4.27	6.42	0.084	...	0.050	...	0.31	0.18	0.06
HD104745	3.02	5.13	0.076	0.310	0.048	...	0.34	0.16	0.06
HD108849	4.55	7.58	0.100	...	0.061	...	0.37	0.41	0.31
HD109225	2.91	5.02	0.065	...	0.051	...	0.31	0.14	0.11
HD109467	3.63	5.09	0.071	...	0.055	...	0.15	0.06	0.07
HD113285	4.96	7.30	0.086	...	0.056	...	0.51	0.52	0.31
HD114691	4.48	6.47	0.096	...	0.055	...	0.24	0.23	0.32
HD126903	3.95	5.57	0.085	...	0.060	...	0.12	0.09	0.08
HD163783	2.25	3.41	0.092	...	0.049	...	0.25	0.17	0.09
HD173604	4.03	4.80	0.075	...	0.042	...	0.17	0.20	0.12
HD183847	4.20	5.13	0.096	...	0.040	...	0.22	0.32	0.19

define an equivalent measure of the strength of CO in the H band, called CO_H. This index is the absorption strength in magnitudes of all the features under a smooth fit to high points of the spectrum between 1.55 and 1.7 μm; in this wavelength interval the absorption features are mostly from CO. The values of CO_H and CO_K are displayed in Table 5. For comparison, Table 5 also gives values of CO_t, the continuum-corrected index derived in Paper I from the photometric CO index via $CO_t = CO + 0.29\,(H-K)$.

The left-hand panel of Figure 9 compares the index CO_K to CO_t. Bulge and local giants are plotted as filled and open symbols, respectively. As expected, CO_K is tightly correlated with CO_t. The CO_K index is plotted against $J-K$ in the right-hand panel of Figure 9. In the mean the bulge M giants have CO_K 0.03 mag larger than the solar neighborhood stars; as a result, a bulge star that has an overall SED like that of a nearby giant would have bluer $H-K$ colors from the stronger CO absorption. This is in the opposite sense to the color differences between bulge and local giants in the $J-H$, $H-K$ plane (Papers I and II), confirming our earlier conclusion that CO is not the cause of the observed color differences.

Figure 10 displays the behavior of the CO_H index. In the first panel, CO_H is plotted against $J-K$, while in the second panel the CO_H index is plotted against CO_K. Unlike the case with CO_K, the absorption in the H band does not show any clear trend with color, nor are there any real differences between the bulge and local M giants. This may be due to the effects of H_2O absorption throughout the H-band spectra as well as that of the unidentified absorption discussed below in § 5. Figure 10 shows that CO is not a significant influence on the level of the H band; we will further discuss this below in § 5.

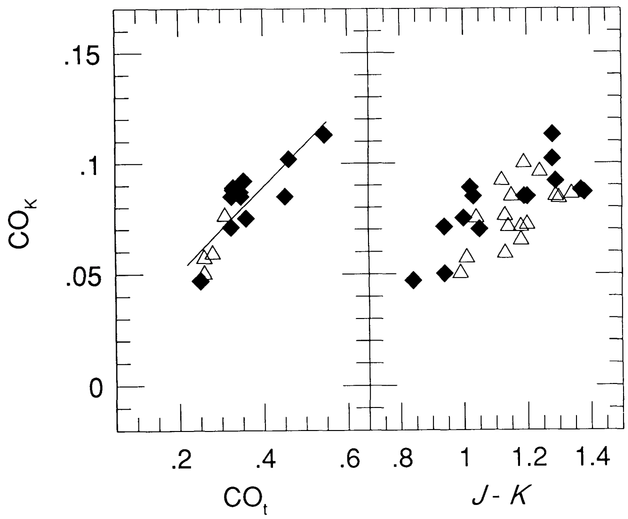

FIG. 9.—Spectrophotometric measure of CO absorption in the K band. Symbols are as in Fig. 6. *Left panel:* Spectrophotometric index CO_K against corrected filter index CO_t from Paper I; *right panel:* CO_K against $J-K$ color.

In Papers I and II, the CO strengths of the bulge M giants were used to measure the metal abundance. This was based on an empirical relation between the photometric CO index and $J-K$ color for clusters of known metallicity. An uncertainty in this procedure of is the fact that bulge M giants are known to be significantly less luminous than local giants of the same spectral type or $J-K$ color (Frogel & Whitford 1982; Whitford 1985; Papers II and III; Frogel & Terndrup 1991). Since the CO strength is sensitive to luminosity (i.e., gravity) in field stars of the same spectral type or color (Baldwin, Frogel, & Persson 1973), it is possible that the previous metallicity differences between bulge and field giants were underestimated as luminosity differences were only indirectly considered.

We can now quantitatively estimate the difference in gravity between the bulge and local M giants via the equation

$$\log g = \log M - \log L + 4 \log T_{\mathrm{eff}} ,$$

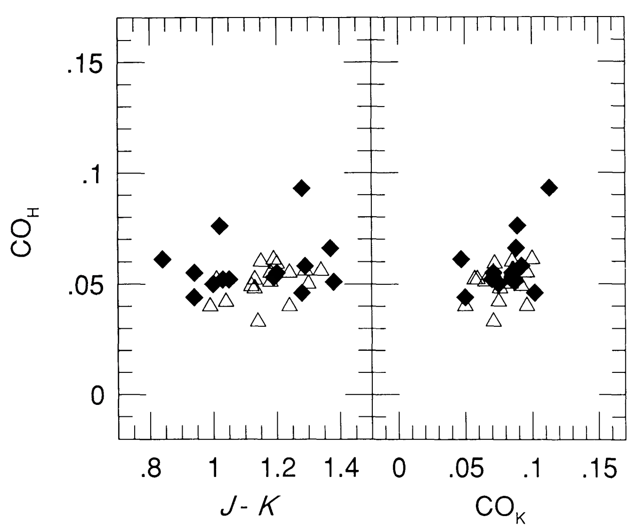

FIG. 10.—Spectrophotometric measure of CO absorption in the H band. *Left panel:* Correlation of spectrophotometric index CO_H against $J-K$ color; *right panel:* correlation with CO_K.

which follows from the basic equations $g \propto M/R^2$ and $L \propto R^2 T_{\rm eff}^4$. $J-K$ is a good indicator of temperature for both bulge and field giants that are not large-amplitude variables (§ 4.1). The conversion from $J-K$ to temperature appears to be identical for both types of stars. Therefore, if we compare CO strengths for bulge and field giants of the same $J-K$, there should be no temperature difference. Based on recent estimates of the absolute magnitudes of field giants, Frogel & Terndrup (1991) show that the field giants are about 0.5 mag brighter than bulge giants of the same $J-K$, and 1.8 mag brighter at the same spectral class. Furthermore, since bulge giants are old (10^{10} Gyr) stars only now reaching AGB luminosities (because they are metal-rich), they have a lower mass than field giants; we adopt 1.1 $M_\odot$ for the bulge stars and 1.8 $M_\odot$ for the local giants. These values are appropriate for old, metal-rich bulge stars and nearby giants of age like the Sun (Terndrup 1988; VandenBerg & Laskarides 1987). Therefore, we see from the above equation that the effect of the differences in mass and luminosity cancel each other; the net effect is that $\Delta(\log g) = 0.0$. We conclude that the analysis of Papers I and II stand and that the abundance difference based on CO is consistent with that from the atomic lines. On the other hand, if the calculation is made comparing bulge and field stars of the same *spectral class*, the above equation yields $\Delta(\log g) = +0.6$, bulge stars having the higher gravity, because now the bulge stars are both less luminous and hotter than the field stars; most of the gravity difference comes from the fainter luminosity in the bulge stars.

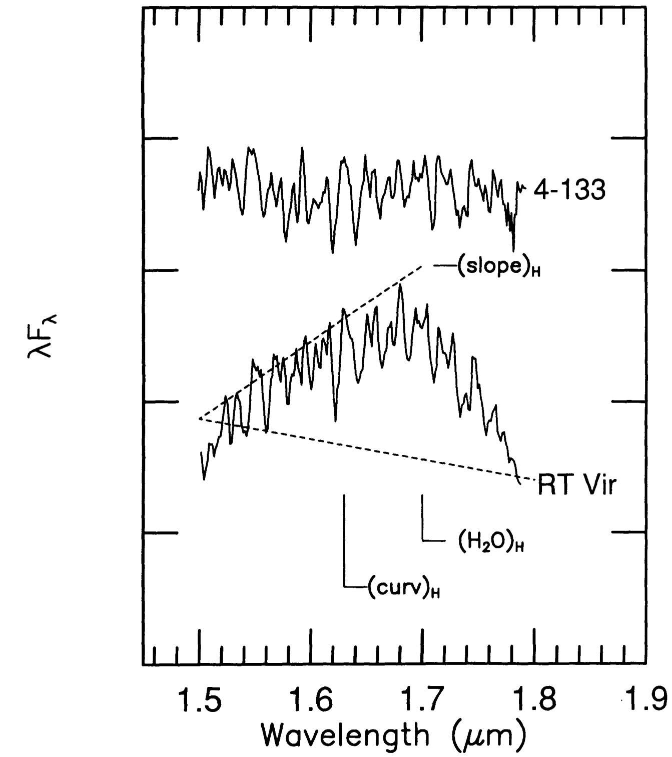

FIG. 11.—Detail of the H spectrum of a bulge and a local M giant, and definition of measures of H-band shape and curvature. See text for details.

5. THE EFFECT OF H_2O AND CO ON THE *JHK* COLORS

In Paper I we advanced the idea that absorption by the H_2O molecule is the primary cause of the differences in the $J-H$, $H-K$ colors between stars in Baade's Window and field giants. Data for bulge fields at other latitudes (Paper II), however, revealed that while H_2O absorption must certainly play a role in determining the *JHK* colors, the differences in these colors between M giants at different latitudes was nearly independent of the measured H_2O strength. The filter technique employed to measure the strength of the 1.9 μm H_2O band becomes rather insensitive to H_2O absorption for the warmer stars in the sample since it measures absorption only in the wing of the band which rapidly weakens with increasing temperature. With the aid of the new spectrophotometric data presented in this paper, we can define a more sensitive measure of the 1.9 μm H_2O band and can examine the overall shape of the H band spectrum.

Figure 11 shows two H-band spectra: that of RT Vir, with moderately strong H_2O absorption, and 4-133, a Baade's Window M giant with little or no absorption. We are interested in three quantities to characterize these spectra: the continuum slope freed as much as possible from the effects of H_2O absorption, the amount of H_2O absorption determined more precisely than is possible with the filter technique, and the curvature of the spectrum. From the plots of the overall energy distributions of the M giants, we can see that the effect of H_2O absorption is more readily visible on the longward side of the H band than the shortward side. In the later type stars the result of strong H_2O absorption is to make the H-band spectrum quite curved. The effect of an absorber other than H_2O, if its strength were more or less independent of wavelength within the H band, might be to reduce the curvature caused by H_2O.

Figure 11 illustrates how we measure the slope, the curvature, and the H_2O absorption in the H band. To measure the continuum slope between 1.50 and 1.70 μm, we draw a straight line through most of the high points in the spectrum between these two wavelengths and define the slope as $(\text{slope})_H = [F_\lambda(1.7) - F_\lambda(1.5)]/F_\lambda(1.5)]$, where the values of F_λ are for the straight line rather than the actual spectrum. For stars with the greatest amount of H_2O absorption, the H spectrum shows curvature even at 1.5 and 1.7 μm, so it is necessary to extrapolate slightly to get the needed values.[5] A second line is drawn connecting the observed high points of the spectrum near 1.5 and 1.8 μm. The slope of this line is strongly influenced by H_2O absorption at the red end of the band and should be considerably more sensitive to H_2O absorption than the filter determined index of Papers I and II. This absorption is measured by the relative change in flux at 1.7 μm of the two lines: $(H_2O)_H = [F_\lambda(1.7)_c - F_\lambda(1.7)]/F_\lambda(1.5)$, where $F_\lambda(1.7)_c$ is the flux value of the straight line between 1.5 and 1.8 μm at 1.7 μm and the value without a subscript is for the actual spectrum. The third quantity, $(\text{curv})_H$, measures the curvature of the H-band spectrum and is defined as the height of a local maximum at 1.63 μm above the line connecting the 1.5 and 1.8 μm points. Values for these three quantities are given in the last three columns of Table 5. Also included in the seventh column of Table 5 are filter H_2O indices for many of the stars in our sample (Paper I).

Figure 12 illustrates the relevant correlations between the three quantities just defined and the filter H_2O index. Figure 12*a* shows a tight correlation between the $(H_2O)_H$ and $(\text{curv})_H$

[5] Obviously, the star to star differences in the slopes measured are independent of the extrapolation as we could have chosen fiducial wavelengths closer to the center of the H band to completely avoid the effects of H_2O absorption.

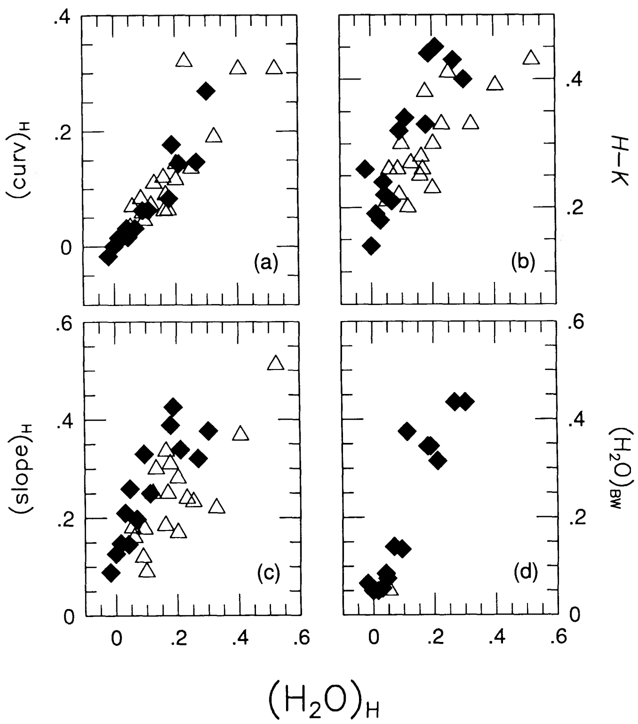

FIG. 12.—Measures of the slope and curvature of the H spectra and spectrophotometric H_2O index for bulge and local M giants. See text for details.

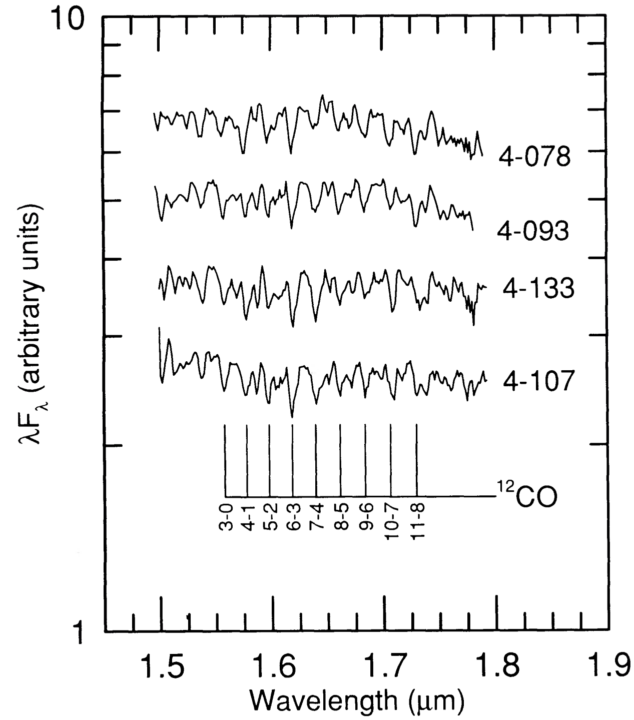

FIG. 13.—Detail of the H spectra of the four bulge M giants in Fig. 4. Stars have nearly the same $J-K$ and are arranged in order of decreasing $J-H$ and increasing $H-K$.

with no difference between the bulge and field giants. Figures 12*b* and 12*c* show that the field giants have stronger $(H_2O)_H$ at the same $H-K$ or continuum slope than do the bulge stars. Figure 12*d* indicates that the filter and spectroscopic H_2O indices are tightly correlated.

The correlation between $(\text{curv})_H$ and $(H_2O)_H$ indices demonstrates that the overall shape of the H-band spectra is largely determined by H_2O absorption independent of the group of stars being considered: for a given $(H_2O)_H$ there is a single value of $(\text{curv})_H$. However, the fact that at constant continuum slope—or $H-K$—$(H_2O)_H$ is greater in the field than the bulge stars indicates some absorber other than H_2O (aside from H^-) must play a key role in setting the continuum height and thus determining the $J-H$, $H-K$ colors. The reasoning for this conclusion is as follows: H_2O affects the H band much more than the K band. Therefore, if star A has stronger H_2O absorption than star B but both have the same $H-K$ color, then some other agent must be depressing the H band of star B to give it the same value of $H-K$ as star A but with less H_2O.

Could the absorber be CO? We feel that this is unlikely. First of all, the absorption coefficient, expressed in cm^2 g^{-1}, of the second overtone (3–0) CO band is about 100 times weaker than that of the first overtone band (e.g., Kunde 1968). Second, the (3–0) band should affect the shortward side of the H band much more than the longward side. Thus, if this band is strong enough to influence the H band as a whole, then the continuum slope as defined above should be markedly steeper at constant $H-K$ in the bulge giants than in the field stars. This is not the case, as can be seen from the H-band spectra in Figure 13 (enlarged from Fig. 4) which show the gradual depression of the H spectrum near 1.6 μm pointed out above in § 3. Marked on that figure are the locations of the (3–0) and higher bands of the second overtone of CO. There does not seem to be any increase in the strengths of the CO features to match the depression of the spectra from top to bottom. Also, it is worth noting that there is no significant reduction of the continuum longward of the (3–0) band edge at 1.56 μm, in contrast to the (2–0) edge at 2.29 μm.

A final test for the possibility that H_2O or CO or both are at least partially responsible for the difference in JHK colors between bulge and field stars employs the parameter $\Delta(JHK)$, first derived for globular cluster Mira variables (Frogel, Persson, & Cohen 1983). This index measures the departure of a star from the mean field line in a $J-H$, $H-K$ plot along a line drawn at a 45° angle from the star's location to the field line. Corrections for H_2O absorption on the shortward side of the K band and for the single-sideband influence on the H_2O and CO indices were applied following the prescriptions in § III of Paper I. Similar corrections were applied to the mean locus of the local giants as given by Frogel et al. (1978) using the mean H_2O indices of Aaronson, Frogel, & Persson (1978). Only for spectral masses M4–M7 is there sufficient data to examine any correlations between CO_t, H_2O_t, and $\Delta(JHK_t)$. It was found that there is no correlation between CO_t and $\Delta(JHK_t)$. For H_2O_t the correlation with $\Delta(JHK_t)$ is, at best, weak, consistent with the related analysis displayed in Figure 8 of Paper II.

6. CONCLUSIONS

The abundant population of M giants in the Galactic bulge presents us with a number of unresolved problems that directly have to do with the origin and evolution of metal-rich stars and, indirectly, with the origin and evolution of the bulge itself.

With a multichannel infrared spectrometer and an optical CCD spectrograph, we have been able to obtain medium-resolution spectrophotometry for a representative sample of these stars over a wavelength range that encompasses more than 80% of their total energy output. With these new data, we can address some of these unresolved problems.

Direct estimates for the abundances of M giants are difficult to obtain. We know that the K giants in Baade's Window are super–metal-rich: their mean [Fe/H] is about +0.2 with a spread of ~ 1 dex (Whitford & Rich 1983; Rich 1988). For the M giants, the evidence, much of it rather indirect and qualitative, is consistent with a similarly high mean abundance. Such evidence includes the absence of luminous C stars in the bulge, a ratio of late to early M giants considerably greater than that found elsewhere in the Galaxy (e.g., Blanco et al. 1984), the strong CO and TiO absorption bands in the bulge M giants, and their peculiar $J-H$, $H-K$ colors (Papers I and III). A metallicity greater than solar for the M giants is critical in understanding how stars with an age of ~ 10 Gyr can be 1 mag or more brighter than the top of the giant branch of an old stellar population (Frogel & Whitford 1982). A comparison of [Fe/H] values for the K and M giants is necessary to establish the evolutionary link between the two types of stars and to investigate the history of star formation in bulge. Thus it is of considerable importance to determine [Fe/H] for the M giants with as much accuracy as possible.

With the new data presented here we are able, for the first time, to use atomic absorption lines to derive abundances for the bulge M giants. Because of the simplicity of how these lines are formed (Deutsch 1966), abundance values based on them should, in principle, have less uncertainty than those derived from molecular species. We have measured the strengths of lines of Na and Ca in the 2.2 μm spectral region and deduce a mean [Fe/H] of 0.3 for the M giants in Baade's Window. This is in excellent agreement with our earlier estimates and with that for the K giants. Also, this result is strong support for our contention that because of their high metallicity, essentially all of the K giants evolve into M giants and that these M stars are the ones found by the grism surveys (Paper II).

In the course of our analysis of the neutral atomic lines in the spectra of the M giants in Baade's Window, we had to derive values for the temperature and surface gravity. Our best estimates for these values are that at the same spectral type, the bulge M giants are in the mean hotter by 400 K and have higher gravities by 0.6 dex than do local M giants of the same spectral type; for stars of the same $J-K$ color, the differences in gravity and effective temperature are negligible. We have already established that the bulge giants are up to 1.8 mag fainter than local giants of the same spectral type (Frogel & Whitford 1982; Paper I; Frogel & Terndrup 1991). We have also determined that bulge and field giants of the same $J-K$ color have the same effective temperature. A reexamination of abundance values from CO absorption bands that makes use of these new determinations yields results completely consistent with those obtained from the atomic lines. This is true for both CO band strengths measured from the spectral scans and those measured from filter photometry (Paper I).

A problem that remains unresolved is the difference in width of the [Fe/H] distribution between K and M giants. Rich's (1988) optical spectroscopy and Terndrup's (1988) optical photometry both indicate a FWHM of ~ 1 dex in [Fe/H] for K giants in Baade's Window. For the M giants, on the other hand, all estimates for the abundance distribution, including that from the Na I and Ca I lines, indicates a significantly smaller spread, about a factor of 2. This result does not appear to be due to an insensitivity of the various techniques since, except for that based on the atomic lines, measurements exist for M giants at six latitudes in the bulge and easily reveal differences in the mean abundances of the fields, as measured by several independent criteria (Papers II and III). The optical data for the K giants indicate that the spread in [Fe/H] within Baade's Window should be comparable to or greater than the spread between the fields we have observed. Our *intra*field spread for the M giants (Papers II, III, and the present one) is considerably less than the *inter*field spread determined with the same analytic techniques. A possible cause for concern is the fact that we are only observing M giants: Could the most metal-poor of the K giants studied optically not evolve into M giants? While this is possible, it must apply to only a relatively small fraction of the stars. There are several reasons for this. First of all, if they do not become M giants, they must then become K giants with $M_{\rm bol} < -3.0$ or a K magnitude brighter than 9. The brightest K giants tend to be significantly fainter than this (Frogel, Whitford, & Rich 1984). Second, as pointed out in Paper II, inspection of the direct photographic plates for the various fields or the optical photometry of Arp (1965) and of van den Bergh & Herbst (1974) reveal few if any bright stars red enough to be of K type but not so red as to have already been selected as an M star.

Finally, with calibrated spectrophotometry that spans a range of nearly a factor of 6 in wavelength we have been able to investigate differences in the overall shapes of bulge and field M giant SEDs. Of particular interest is the so-called H-band bump, or lack of it, that is usually attributed to a minimum in the H^- opacity. Bulge giants have $J-H$, $H-K$ colors that clearly separate them from field giants. In Paper I we argued that this separation is due to excess absorption in the H band. The opacity due to the H_2O molecule seemed to be a likely candidate for dilution of the effect of the H^- opacity minimum (cf. Alexander et al. 1989; Bessell et al. 1989). However, our analysis of the shape and level of the H-band spectra and other arguments presented in this paper are inconsistent with the hypothesis that H_2O opacity (or CO opacity) is the primary explanation for the difference in the JHK colors of bulge and field M giants. Furthermore, the difference cannot be attributed to enhanced H^- opacity since as long as H^- remains the dominant opacity source (Tsuji 1966) the relative opacities in the J, H, and K bands keep the same ratio as the metallicity changes up or down. Finally, we make one speculative suggestion: all of our measures of H_2O strength are based on strong, saturated lines that blend together to act as a pseudocontinuous absorber. However, H_2O lines occur throughout the JHK bands (e.g., Alexander et al. 1989) with their effect in the H band of the greatest relative strength. Suppose that the enhanced [M/H] in the bulge stars results in enhancement of the weaker H_2O lines in the H band but leaves the strongest lines, i.e., those that go into the H_2O indices that we measure, relatively unaffected. Could the net effect of this be to cause the depression in the H band that is observed in the bulge stars? Both weak H_2O lines and the forest of weak atomic lines of many elements throughout the spectra of metal-rich stars (on the linear part of the curve of growth) would be most likely to have the greatest effect where the opacity minimum of H^- permits seeing deeper into the stellar atmosphere.

We hope that the new data we have presented in this paper will serve as an impetus to those who are actively engaged in

research on molecular opacities and their effect on the emergent stellar flux from cool giants to provide us with insight as to the problems that our research has raised.

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