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PHOTOMETRIC STUDIES OF COMPOSITE STELLAR SYSTEMS. II. OBSERVATIONS OF H_2O ABSORPTION AND THE COOLEST STELLAR COMPONENT OF E AND S0 GALAXIES

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ABSTRACT

Multiaperture observations of the H_2O absorption feature near 2.0 microns are presented for the nuclei of 37 early-type galaxies, for five globular clusters, and for a selection of stars. The H_2O absorption is a sensitive function of effective temperature, and provides a strong constraint on the contribution of the very coolest stars to integrated galaxian light. In combination with the luminosity-sensitive CO absorption, the large H_2O absorption found in galaxies indicates that at 2 microns a significant contribution from a stellar giant component at least as late as M5 in spectral type is present. For our limited data sample, the amount of H_2O absorption shows no dependence on absolute magnitude for galaxies with $M_V \leq -20$, and no dependence on projected aperture size in the range $1.0 \geq A/D(0) \geq 0.1$. The observations are compared with recently published synthesis models of Tinsley and Gunn and of O'Connell; best agreement is found with O'Connell's models. It does not appear that a significant contribution of carbon stars can account for the discrepancy between the infrared data and the models of Tinsley and Gunn.

Subject headings: clusters: globular — galaxies: photometry — galaxies: stellar content — infrared: sources

I. INTRODUCTION

Observations and stellar-synthesis models of early-type galaxies have shown that most of the visible and infrared light from these galaxies is supplied by a giant-dominated stellar population (O'Connell 1974, 1976*b*; Tinsley and Gunn 1976; Whitford 1977; Frogel *et al.* 1975*a*, *b*, 1978, hereafter Paper I). The various photometric indices used by these authors establish that the contribution of main-sequence stars to the total flux at 2 μm is less than 10%. However, the detailed structure of the giant branch remains uncertain. For example, M6 III stars contribute 37% of the flux at 2.2 μm in the model of O'Connell (1976*b*) that fits the infrared data best, but only 12% in the best-fitting model of Tinsley and Gunn (1976). Yet the CO indices of these models differ by only 0.02 mag (Paper I). A spectral feature which is sensitive to effective temperature in late-type stars, and can therefore set constraints on the luminosity function of the giant branch, is the broad stellar absorption band due to H_2O centered at 1.9 μm (Johnson and Méndez 1970; Frogel 1971; Baldwin, Frogel, and Persson 1973). In this paper we first discuss the dependence of the H_2O absorption on stellar effective temperature and luminosity. We then present multi-aperture H_2O observations of the nuclei of 37 early-type galaxies and five globular clusters, and compare the data with those of Paper I and with the results of stellar-synthesis models.

II. OBSERVATIONS

The equipment and techniques used for these observations are described fully in Paper I. Briefly, all measurements were made with an InSb detector cooled to 55 K. To measure the strength of the H_2O absorption, two filters cooled to either 77 K or 55 K were used. They have effective wavelengths and full widths at half-maximum of 2.00 (0.08 μm) and 2.20 (0.11 μm); the latter filter is the "continuum" filter used in measuring the CO index (Paper I). Thirty-seven galaxies selected from Paper I were observed in the spring of 1976 with the 60 inch (1.5 m) and 100 inch (2.5 m) telescopes on Mount Wilson, and the 200 inch (5 m) Hale reflector. Most of these observations were made at the same time as the CO and *JHK* observations of Paper I. The stellar calibration of the H_2O index was determined with these telescopes and with the 60 inch (1.5 m) Tillinghast reflector of Mount Hopkins, Arizona. Several globular clusters were observed on the 0.9 m telescope of Kitt Peak National Observatory and the 1.5 m telescope at Cerro Tololo Inter-American Observatory. As in Paper I, all

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TABLE 1

H_2O INDICES OF STARS

STANDARDS			SELECTED HIGH LUMINOSITY STARS			OTHER LATE-TYPE STARS			
HR	SPECTRAL TYPE	H_2O INDEX	NAME	SPECTRAL TYPE	H_2O INDEX	NAME	SPECTRAL TYPE	H_2O INDEX	CO INDEX
0134	K0 III	0.025	HR 3027	M2 II - III	0.04	R Aur	Mira	0.29	0.45
0923	K0 III	0.025	HR 4008	M0 III	0.05	U Ori	Mira	0.60	0.31
1552	B2 III	0.00	HR 4336	M2 III	0.06	W Ori	C5,3	0.19	0.04
1698	K3 III	0.03	HR 4902	M3 III	0.08	T Cnc	C4,5	0.23	-0.06
3304	K5 III	0.035	BK Vir	M7 III	0.35				
3403	K2 III	0.035	RT Vir	M8 III	0.37				
3427	K0 III	0.03	BC Cyg	M4 Ia	0.20				
4039	d F5	0.02	AZ Cyg	M2 Ia	0.18				
4550	G8 VI	0.02	KY Cyg	M4 Ia	0.21				
4608	G8 III	0.02	+9° 3920	M2 III	0.06				
4689	A2 V	0.00	+29° 3730	M4 III	0.10				
6092	B5 IV	-0.01	+35° 4138	M3 III	0.06				
6136	K4 III	0.02	+59° 2541	M2.5 III	0.07				
6228	K5 III	0.04	+64° 1842	M2 II	0.10				
7001	A0 V	0.00	+42° 1065	M0 III	0.06				
8498	K3 II - III	0.03							
8551	K0 III - IV	0.02							
HD 132950	K	0.035							

measurements were made with the focal plane apertures centered on the optical nuclei, and the visual centering was confirmed by maximizing the infrared signal. Sky chopping was always in the north-south direction with the "reference" beam typically two to three aperture diameters away from the "signal" beam. Most of the measurements were made on only one night. Repeatability of the standards, however, shows that the error from uncertainties in the calibration, combined with statistical measurement error and systematic errors arising from beam profile effects, are on the order of 0.02 mag. A full discussion of the sources of error in the measurements of the CO index was given in Paper I, and applies equally well here.

III. THE STELLAR DATA

A grid of 17 standard stars was set up in a manner similar to that described in Paper I. The H_2O indices of these stars are referred to that of α Lyrae, which is defined equal to 0.00, and are given in the first part of Table 1. The internal accuracy of the grid is judged to be close to ± 0.01 mag. The second part of Table 1 lists values of the H_2O index for high-luminosity stars, and can facilitate transfer between ours and other photometric systems. Similar observations of dwarf stars are presented by Persson, Aaronson, and Frogel (1977). In the last part of Table 1, CO and H_2O indices of a few Mira and carbon stars are listed. Although high-resolution scans (Johnson and Méndez 1970; Frogel and Hyland 1972) show that carbon stars have very strong CO and no H_2O absorption, the extremely red continua of these stars cause our measured indices to indicate the opposite.

Table 2 gives the adopted mean relationships among the H_2O index and color and spectral type for giant and dwarf stars. They are based on the data of Table 1 and on unpublished observations of more than 50 other stars. Values of $V - K$ are from Paper I. It is apparent from Table 2 that, for K and M dwarfs and giants, the H_2O index depends strongly on effective temperature. Furthermore, for stars with spectral types between M0 and M6, it depends strongly on luminosity, but in the opposite sense to that of the CO index; viz., the H_2O index is stronger in dwarfs than in giants.

IV. DISCUSSION OF THE GALAXY AND GLOBULAR-CLUSTER DATA

The observed values of the H_2O index for the galaxies and globular clusters are presented in Tables 3 and 4, respectively. Unless noted otherwise, the 1 σ_m errors in the photometry are ± 0.02 mag. For the values of A_v appropriate to the objects in these tables, no reddening corrections need be applied to the H_2O

TABLE 2

ADOPTED MEAN H_2O INDICES

Giants			Dwarfs		
Spectral Type	$V - K$	H_2O Index	Spectral Type	$V - K$	H_2O Index
G5......	2.08	0.02	F8......	1.25	0.02
G8......	2.16	0.02	G5......	1.50	0.02
K0......	2.35	0.03	K0......	1.75	0.03
K1......	2.48	0.03	K1......	2.00	0.03
K2......	2.59	0.03	K2......	2.25	0.03
K3......	2.92	0.03	K3......	2.50	0.04
K4......	3.24	0.03	K5......	2.75	0.04
K5......	3.67	0.04	K6......	3.00	0.05
M0......	3.74	0.05	K7......	3.25	0.06
M1......	3.90	0.05	M0......	3.50	0.08
M2......	4.16	0.06		3.75	0.11
M3......	4.63	0.08	M1......	4.00	0.13
M4......	5.34	0.10	M2......	4.25	0.17
M5......	6.20	0.12 ± 0.03	M3......	4.50	0.19
M6......	7.20	0.20 ± 0.05	M4......	4.75	0.21
M7......	...	0.36 ± 0.05	M5......	5.00	0.22
				5.25	0.23
			M6......	5.50	0.24
				5.75	0.25
				6.00	0.26
			M7......	6.25	0.27
				6.50	0.28
				6.75	0.30
			M8......	7.00	0.31
				7.25	0.32
				7.50	0.34

NOTE.—Owing to the small number of giant stars observed with spectral types M6 and later, we attach an uncertainty of ± 0.05 mag to the mean H_2O indices. In addition, we find evidence for a substantial dispersion in the H_2O index at a given color for these late stars. The uncertainties are approximately ± 0.02 mag elsewhere.

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TABLE 3

H_2O INDICES IN EARLY-TYPE GALAXIES

Galaxy / Type (1)	Telescope (inches) (2)	Aperture Diameter (arc sec) (3)	Log A/D(0) (4)	H_2O INDEX (5)
NGC 1600 E4	200	15	-0.69	0.14
NGC 1700 E3	200	15	-0.75	0.125
NGC 2300 E3	200	15	-0.68	0.135
	60	48	-0.18	0.11
NGC 2549 $S0_1(7)$	200	15	-0.88	0.115
	60	48	-0.38	0.115
NGC 2634 E1:	200	15	-0.50	0.145
	60	48	+0.01	0.105 ±0.04
NGC 2655 SAB(s) 0	200	15	-1.14	0.11
	60	48	-0.63	0.105
NGC 2672 E2	200	15	-0.65	0.135
NGC 2768 E6	200	15	-0.98	0.115
	60	48	-0.48	0.115
NGC 2974 E4	200	15	-0.75	0.135
NGC 3115 E7/$S0_1(7)$	200	15	-1.04	0.13
	84	37.5	-0.64	0.13
	60	48	-0.54	0.135
	36	106.4	-0.19	0.145
NGC 3193 E2	200	15	-0.78	0.10
NGC 3377 E6	200	15	-0.90	0.10
NGC 3379 E0	200	15	-0.96	0.11
	60	48	-0.46	0.105
NGC 3384 $SB0_1(5)$	200	15	-1.01	0.10
NGC 3607 $S0_3(3)$	200	15	-0.83	0.115
NGC 3608 E1	200	15	-0.70	0.10
NGC 3998 $S0_1(3)$	200	15	-0.83	0.12
NGC 4278 E1	200	7.5	-1.17	0.16
	200	15	-0.87	0.145
	200	16.5	-0.82	0.105
	60	48	-0.36	0.09
NGC 4283 E0	100	30	-0.23	0.07
NGC 4365 E3	200	15	-1.09	0.125
NGC 4374 E1 pec	200	7.5	-1.28	0.12
	200	15	-0.98	0.09
	60	48	-0.48	0.115
NGC 4382 $S0_1(3)$	200	15	-1.20	0.11
NGC 4406 E2	200	7.5	-1.37	0.095
	200	15	-1.07	0.115
	60	48	-0.57	0.135
NGC 4459 $S0_3(3)$	200	15	-0.81	0.12
NGC 4472 E2	200	7.5	-1.56	0.15
	200	15	-1.26	0.125
	200	16.5	-1.22	0.105
	60	48	-0.75	0.10
NGC 4478 E2	200	15	-0.65	0.125
NGC 4486 E0	200	7.5	-1.48	0.145
	200	15	-1.18	0.125
	60	48	-0.68	0.105
NGC 4486A —	200	7.5	---	0.085
	200	15	---	0.075
NGC 4486B E0	200	7.5	-0.40	0.12
	200	15	-0.10	0.065
NGC 4494 E1	100	30	-0.58	0.13 ±0.04
NGC 4649 E2/S0	200	15	-1.10	0.12
NGC 4889 E4	200	15	-0.71	0.125
NGC 5813 E1	200	15	-0.86	0.095
	100	30	-0.56	0.095
NGC 5846 E1	100	30	-0.60	0.155
	60	48	-0.40	0.11
NGC 5866 $S0_3(8)$	100	30	-0.66	0.135
NGC 5982 E3	200	7.5	-0.95	0.095
	200	15	-0.65	0.125
	100	30	-0.35	0.135
NGC 6702 E2	100	30	-0.18	0.075

NOTE.—The values of log $A/D(0)$ refer to the aperture size in units of the major diameter $D(0)$ (de Vaucouleurs and de Vaucouleurs 1964). The morphological types were made available to us by Dr. A. Sandage (1977, private communication). The 1 σ_m errors in the H_2O indices are ± 0.02 mag unless noted otherwise.

indices. Unlike the K-correction for the CO index, where the absorption feature is shifted out of the filter bandpass for $z > 0$, the center of the H_2O band is shifted *into* the filter bandpass for $z < 0.05$. An analytic redshift correction based on stellar observations could not be determined, as in Paper I, because the data require significant extrapolation past the wavelength of atmospheric cutoff. An attempt to derive the K-correction empirically, as was done in Paper I for the CO index, is hampered by the more limited sample of galaxies and the apparently small size of the correction. Since the indicated result was $0 \leq K_{H_2O} < 1.3\,z$, and only five galaxies in Table 3 have redshifts $z > 0.01$ (the largest being $z = 0.022$), we have chosen to apply no redshift correction to the data.

TABLE 4

H_2O INDICES IN GLOBULAR CLUSTERS

Cluster	Aperture Diameter (arcsec)	[Fe/H]*	H_2O Index
M3..........	105.	−1.5	0.01
M13..........	105.	−1.6	0.035
M15..........	105.	−1.9	0.035
M69..........	66.4	> −0.4	0.07
M92..........	105.	−2.2	0.025

* For M3, M13, M15, and M92, [Fe/H] is from Hesser, Hartwick, and McClure 1976. For M69, [Fe/H] is an estimate based on the results of Hartwick and Sandage 1968.

In Figure 1 the data from Table 3 are plotted as a function of log $A/D(0)$. No obvious dependence of the H_2O index on radius is seen in this diagram. As was done for the CO data of Paper I, a least-squares fit to the multiaperture data for each galaxy was made, and the resulting values for the individual slopes were averaged. The mean change in the H_2O index per unit change in log $A/D(0)$ is -0.04 ± 0.02 mag. Thus for our limited sample we find no significant dependence of the H_2O index on radius.

We have also searched for a dependence of the H_2O index on galaxian absolute magnitude. Table 5 presents a binning of the 15″ aperture data into the same M_V bins as in Paper I. It is apparent that no significant dependence of the H_2O index on M_V exists for $M_V < -19$. Although the ordering by M_V is also an ordering by increasing z, and no redshift correction has been applied, the largest allowable correction will not significantly affect this conclusion. This result differs from that of O'Connell (1976*a*), who found that a Ca II + TiO index, which also increases toward late spectral type for M giants, decreases with increasing galaxian luminosity for $M_V < -19$. Radial gradients in either index are not likely to affect this comparison, since the aperture size used by O'Connell is close to ours. This difference remains if we restrict our sample to only those 10 galaxies observed in common with O'Connell. This and other absolute magnitude effects will be discussed further in Paper III (Persson, Frogel, and Aaronson 1978).

Figure 2 displays the relationship between the H_2O data of Tables 3 and 4 and the corrected CO and broad-band color data from Paper I for the same or similar aperture size. Also shown are the mean relationships from Table 2. The relative location of the galaxies on the H_2O versus $V - K$, $J - H$, and $H - K$ plots is determined by the fact that we are sampling the light of a composite stellar population. Thus, as was pointed out in Paper I, the $V - K$ color is dominated by hotter members of the population than is the $H - K$ color. This accounts qualitatively for the relatively large displacement of the galaxy data from the mean relation for giants in the H_2O versus $V - K$ plot. Now, the data of Paper I showed that the 2.2 μm radiation from these galaxies is dominated by giant stars. Since the measured strength of the H_2O indices for these galaxies corresponds to that of an M5 III star, we conclude that late M giants must also make a significant contribution to the infrared light of early-type galaxies. O'Connell (1976*a*, *b*) came to a similar conclusion on the basis of his Ca II + TiO measurements.

In order to put this result on a more quantitative basis, we compare the predictions of the models of Tinsley and Gunn (1976, hereafter TG, model A) and O'Connell (1976*b*, hereafter OC, model C) with the data of Table 3. This comparison is presented in Table 6, where the mean observed values are from Table 7 of Paper I and from Table 5 of this paper. The percentage contributions to the light at 2 μm coming from three stellar "bins" were computed for the two models, and the results are listed in the table. As was concluded in Paper I, the relative importance of late M giants in the OC model compared with the TG model to leads better agreement with the observations.

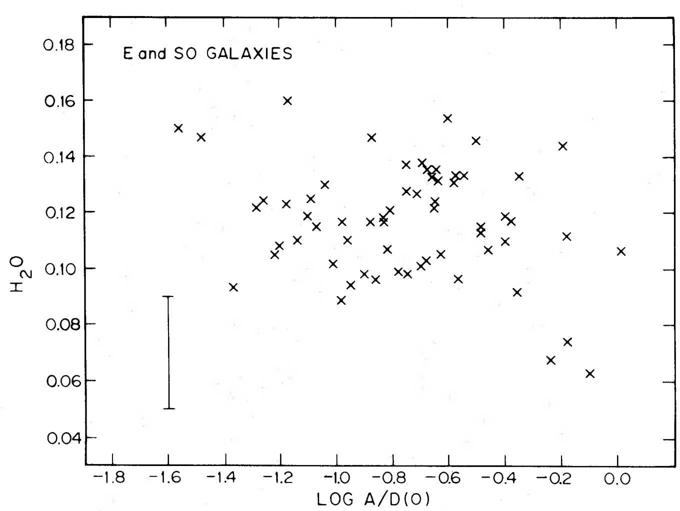

FIG. 1.—The H_2O indices from Table 3 are plotted as a function of log $A/D(0)$

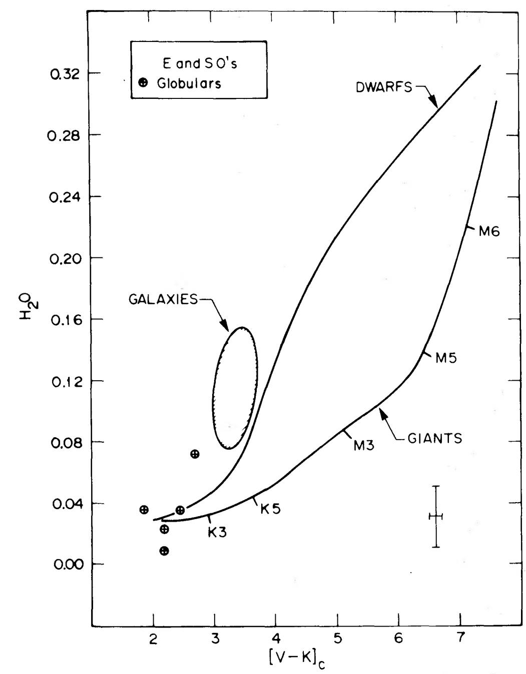

FIG. 2*a*

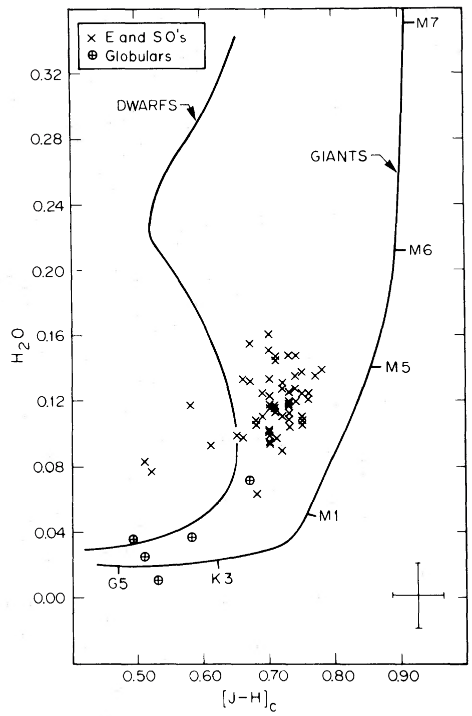

FIG. 2*b*

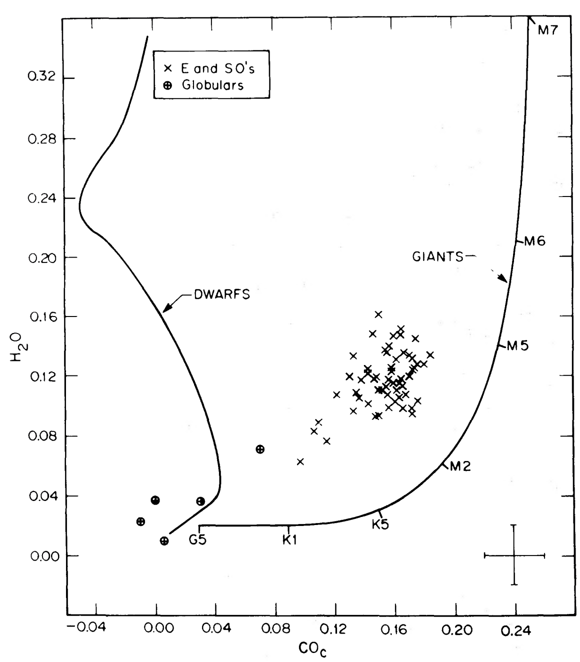

FIG. 2*c*

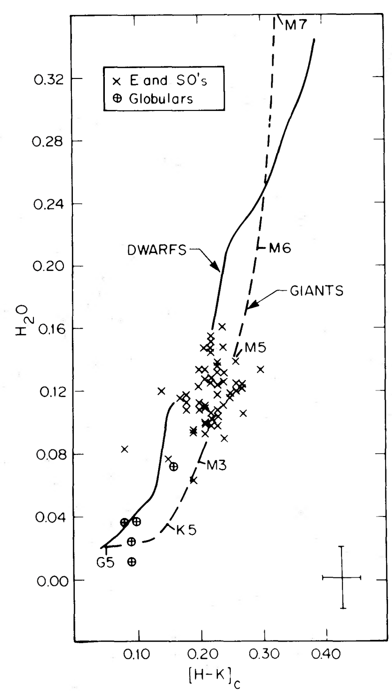

FIG. 2*d*

FIG. 2.—The H_2O indices from Tables 3 and 4 are plotted against the corrected CO indices and broad-band colors from Paper I. Mean relations shown for giant and dwarf stars are taken from Table 2 and from Paper I. The behavior of the mean relationships for dwarf stars is discussed by Persson *et al.* (1977), and the dependence of $J - H$ on T_{eff} for dwarfs is discussed by Mould and Hyland (1976). The dependences of the H_2O index on colors for late-type stars (M5 and beyond) show large dispersion. Galaxy measurements from Table 3 are not plotted unless data at similar aperture sizes are available from Paper I. In the H_2O versus $V - K$ plot, all such points lie within the ellipsoid labeled "galaxies."

TABLE 5

MEAN H_2O INDICES FOR GALAXIES WITH WELL-DETERMINED DISTANCES

$M_{V1.0}$ Limits	No.	⟨z⟩	H_2O Index*
$M_V < -22.8$	3	0.0170	0.13 (±0.01)
$-22.8 \le M_V < -21.8$	9	0.0058	0.12 (±0.02)
$-21.8 \le M_V < -20.8$	8	0.0037	0.115 (±0.01)
$-20.8 \le M_V < -19.8$	8	0.0033	0.115 (±0.02)

* Indices for an aperture diameter of 15″ were averaged. The errors in parentheses are the dispersions.

TABLE 6

COMPARISON BETWEEN MODELS AND OBSERVATIONS

Index	TG	OC	Observed
H_2O	0.08	0.12	0.12
CO	0.14	0.16	0.16
$V - K$	2.97	3.29	3.33
Contribution to the 2.2 μm light			
M6 III bin	12%	37%	...
K0 III to M5 III bins.....	68%	42%	...
All dwarfs and turnoff stars	20%	21%	...

NOTE.—TG, model A; OC, model C.

For the H_2O index, this occurs because the index increases rapidly in the latest giants.

TG have suggested that the inclusion of carbon stars could improve the fit of their model. Because of the single-sideband nature of the H_2O and CO indices, however, a strong temperature-sensitive term is included, and the indices do not behave in carbon stars as they do in ordinary late-type giants (see § III and Tables 1, 2). Therefore carbon stars alone cannot help, since the addition of any of these stars will drive the CO index, already too small in the TG model, to even lower values. Because of the large H_2O and CO absorption in Mira stars, it appears that some contribution from these to the light at 2 μm could be present. However, we find that no combination of Mira and carbon stars added to the TG model produces as good a fit to the infrared data as does the OC model. Furthermore, the allowable contribution of these stars to the TG model cannot be greater than 15% to the light at 2 μm without producing disagreement with the data.

Finally, as was the case for the data of Paper I, we find no sharp discontinuity between the globular clusters and the galaxies in Figure 2; the globular cluster with the strongest H_2O absorption is M69, the most metal-rich one observed. Detailed discussion of the colors and indices of globular clusters and of individual cluster stars will be presented elsewhere.

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