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THE STRENGTHS OF INFRARED CO AND H_2O BANDS IN LATE-TYPE STARS

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ABSTRACT

The strengths of absorption bands due to H_2O and CO at 2.1 and 2.3 μ have been measured for 163 supergiant, giant, and dwarf stars having spectral types from F2 to M8. The strengths of these bands are shown to correlate with spectral type and luminosity. Photometric indices that measure these band strengths should be useful in classifying late-type stars and determining the integrated spectral type of stellar systems.

Subject headings: infrared — molecules — late-type stars — spectral classification

I. INTRODUCTION

Spectra of about 70 late-type stars in the 2-μ spectral region at resolutions of 32 and 65 Å have been obtained by Frogel and Hyland (Frogel 1971). In this paper observations of 163 stars on an intermediate-band photometric system are presented. Many of these stars were included in the spectroscopic survey. The [2.1 μ] − [2.2 μ] and [2.3 μ] − [2.2 μ] colors are shown to be effective indicators of the absorption band strengths of H_2O and CO, respectively. Relationships between these indices and spectral type are shown to agree with corresponding relationships derived from analysis of the 2-μ spectra. For stellar measurements, however, the filter system has a limiting flux 15 times fainter than that of the spectrometer, even at low resolution.

II. OBSERVATIONS

Three filters, acquired from Optical Coating Laboratories, Inc., Santa Rosa, California, form the intermediate-band system. The effective wavelengths are 2.10, 2.2, and 2.31 μ, and the half-power bandwidths are 0.052, 0.080, and 0.095 μ, respectively. These wavelengths were chosen to facilitate measurement of the absorption strengths of the first overtone band of CO in the vicinity of 2.3 μ and the wings of the H_2O band at 1.87 μ. The transmission curves of these filters are shown in figure 1.

Two indices, designated [2.1 μ] − [2.2 μ], and [2.3 μ] − [2.2 μ], were used to compare the H_2O and CO band strengths, respectively, with the continuum at 2.2 μ. Both indices were formed relative to those of α Lyrae, the primary standard. An additional seven stars were used as secondary standards. To calibrate the indices for these stars, each standard was observed on a number of nights concurrently with α Lyrae.

Observations were obtained at the Cassegrain foci of the Mount Hopkins 60-inch (152-cm), and the Kitt Peak 36-inch (91-cm) and 50-inch (127-cm) telescopes.

A conventional dual-beam infrared photometer, similar to the instrument described by Becklin and Neugebauer (1968), was used for the observations. The PbS detector, focal-plane apertures, and a wide-band ($\Delta\lambda = 0.4\ \mu$) blocking filter were thermally coupled to a reservoir of liquid nitrogen mounted inside an evacuated dewar. The uncooled intermediate-band filters were outside the dewar.

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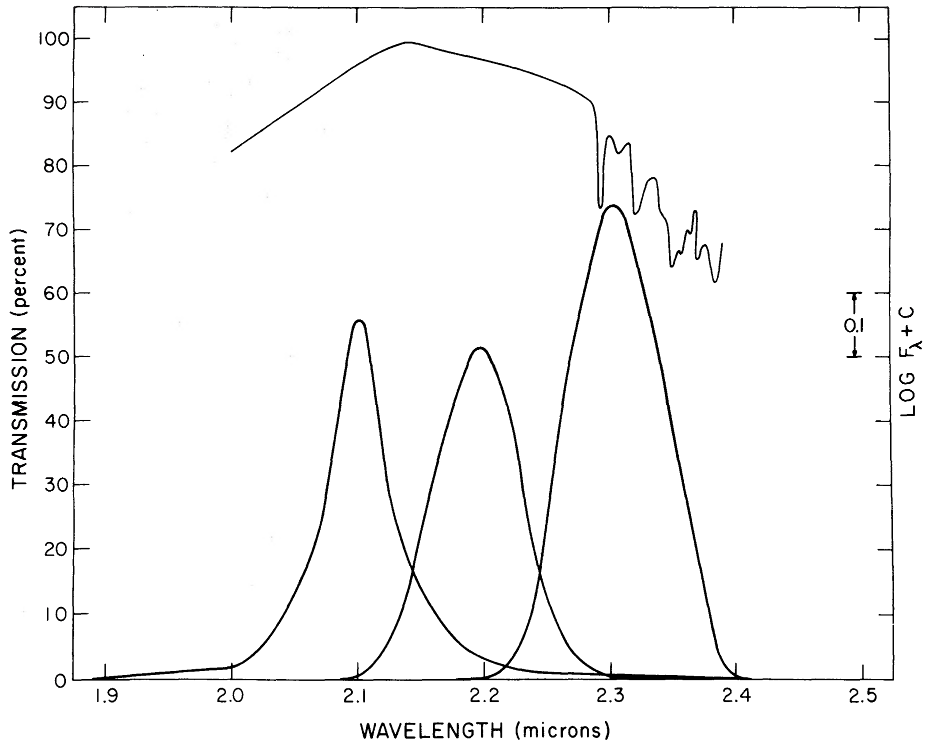

FIG. 1.—Response functions of the intermediate-band filters are shown together with the spectrum of U Ori, a star with strong H_2O absorption. The H_2O absorption extends shortward of 2.14 μ and the first-overtone CO band appears longward of 2.29 μ.

Except for the dwarfs and some of the supergiants, the stars were selected from the Bright Star Catalog. Double stars were included only if it could be determined that the companion would not affect the infrared measurements. Dwarf stars were selected from Johnson (1965) and Greenstein, Becklin, and Neugebauer (1970).

III. RESULTS AND DISCUSSION

The observed sample of 163 supergiant, giant, and dwarf stars includes spectral types F2 through M8. Table 1 summarizes the mean values and the 1 σ errors of both indices, determined from data acquired in 1971 and 1972. Most stars were observed on at least two nights. The colors of the seven secondary standards are also included in table 1. The spectral types, V magnitudes, and $V - K$ colors were taken from the photometry of Johnson *et al.* (1966).

Figure 2 compares the [2.3 μ] − [2.2 μ] color with the spectroscopically determined equivalent width of the first overtone band of CO. Appearing in the figure are all the nonvariable stars observed on the intermediate-band system for which spectroscopic data are available. The quantity W(CO) is the equivalent width of the absorption in the wavelength region from the (2, 0) up to the (5, 3) band head of the first overtone band of $^{12}C^{16}O$ (Frogel 1971). Note that the (2, 0) and (3, 1) band heads of $^{13}C^{16}O$ also contribute to the absorption in this spectral interval. The passband of the 2.31-μ filter encompasses the spectral regions affected by all these band heads as well as the (5, 3) band head of $^{12}C^{16}O$, although the latter feature is below the 15 percent transmission level of the filter. The equivalent-width data and the [2.3 μ] − [2.2 μ] data should, therefore, exhibit a high degree of correspondence, as figure 2 demonstrates.

TABLE 1

INTERMEDIATE-BAND INFRARED PHOTOMETRY OF STARS

Star	Spectral Type	V	V-K	[2.1 μ]-[2.2 μ] Index	[2.1 μ]-[2.2 μ] 1σ Error	[2.3 μ]-[2.2 μ] Index	[2.3 μ]-[2.2 μ] 1σ Error	No. Observations
HR0175	G8III	5.33	...	.023	± .014	.016	± .008	2
HR0207	G0IB	...	...	.005	.012	.016	.018	2
HR0276	G5III	6.32	...	.033	.014	.052	.010	2
HR0337	M0III	2.05	3.88	.019	.001	.105	.001	13
HR0351	G8III	4.66	...	.020	.008	.049	.007	3
HR0356	G8III	...	...	.052	.007	.061	.006	3
HR0371	K1III	...	...	.019	.012	.036	.014	2
HR0399	K0III	4.74	...	.012	.011	.048	.012	1
HR0430	G9III	...	...	.024	.014	.044	.011	2
HR0464	K3III	3.57	2.78	.025	.015	.071	.015	1
HR0469	G8III	...	...	.008	.023	.001	.028	1
HR0603	K3III	2.10	2.91	.015	.012	.094	.012	2
HR0834	K3IB+B9V	3.79	3.70	.012	.010	.115	.011	2
HR0867	M6III	...	...	.044	.006	.123	.005	2
HR0911*	M2III	2.53	4.21	.016	.007	.115	.006	7
HR0921	M4IIIA	3.39	5.32	.024	.012	.122	.013	2
HR0926	K0III	...	...	.010	.009	.055	.009	3
HR0941	K0III	3.81	2.16	.014	.005	.031	.005	3
HR0942	G9III	...	...	.017	.018	.075	.019	3
HR0946	K3III	...	...	.018	.012	.054	.017	2
HR0947	K0III	4.64	...	.012	.009	.055	.009	3
HR0949	K5III	...	...	.017	.010	.072	.010	2
HR0951	K2III	4.37	2.29	.030	.008	.046	.010	3
HR0999	K4III	4.47	...	.025	.009	.093	.008	3
HR1009	M0II	...	...	.020	.017	.149	.015	1
HR1015	K3III	...	...	.030	.009	.083	.009	2
HR1017	F5IB	1.79	1.23	.019	.006	.003	.006	1
HR1030	G8III	3.60	2.02	.001	.005	.016	.006	5
HR1052	K3III	4.38	3.16	.015	.012	.075	.012	2
HR1150	K4III	...	...	.021	.009	.095	.009	3
HR1155	M2IIA	4.48	5.14	.019	.009	.142	.007	2
HR1159	G9III	...	...	.029	.013	.058	.018	2
HR1373	K0III	3.76	2.12	-.036	.010	.018	.011	3
HR1457	K5III	.86	3.67	.017	.003	.100	.003	7
HR1612	K5II +B	3.75	3.60	.021	.006	.096	.004	2
HR1708*	G8III+F	.08	1.86	.018	.001	.029	.001	6
HR1845	M2IB	4.35	5.24	.036	.006	.170	.006	2
HR2061	M1-M2IAB	.42	4.42	.027	.004	.166	.004	2
HR2091	M3.5II	4.25	5.10	.023	.005	.123	.006	2
HR2190	M1IAB	...	...	.035	.008	.108	.007	3
HR2197	M1IA	...	...	.048	.015	.144	.015	1
HR2216	M3III	3.28	4.59	.031	.001	.121	.001	8
HR2219	G8III	4.35	2.41	.020	.011	.038	.008	2
HR2230	G5III	6.09	...	-.001	.024	.005	.025	1
HR2286	M3III	2.87	4.76	.028	.011	.115	.011	2
HR2473	G8IB	2.98	2.76	.025	.007	.085	.009	2
HR2580	K3IAB	3.92	3.47	.047	.012	.149	.017	1
HR2646	M0IAB	3.43	3.92	.027	.016	.143	.016	1
HR2649	K3III	...	...	.009	.006	.102	.005	4
HR2693	F8IA	1.84	1.42	.004	.016	-.020	.026	1
HR2697	K2III	4.42	2.83	.025	.002	.058	.002	4
HR2717	M4III	...	...	.026	.007	.128	.008	3
HR2725	M1III	...	...	.009	.005	.105	.008	3
HR2808*	G8III	...	...	.005	.010	.024	.012	2
HR2821	K0III	3.79	2.33	.019	.015	.029	.015	1
HR2828	G8III	4.99	...	.014	.014	.043	.017	1
HR2864	K2III	4.55	...	.027	.015	.081	.015	1
HR2905	M0III	4.06	3.76	.023	.005	.097	.005	2
HR2943	F5IV-V	.37	1.01	.008	.001	.007	.001	12
HR2970	K0III	3.93	2.31	.006	.013	.037	.012	2
HR2973	K1III	4.29	2.64	.028	.013	.031	.012	2
HR2978	K0III	...	...	.056	.018	.069	.025	2
HR2990	K0III	1.14	2.23	.021	.011	.031	.011	2
HR3249	K4III	3.53	3.37	.015	.007	.090	.006	2
HR3275	K5III	4.25	3.67	.004	.006	.097	.010	2
HR3369	G9III	...	...	.020	.010	.050	.010	1
HR3459	G2IB	4.61	...	.015	.019	.005	.016	2
HR3461	K0III	3.94	2.43	.010	.008	.047	.005	2
HR3612	G8IB-II	4.56	...	.034	.011	.054	.010	2
HR3621	G8III	...	...	.020	.011	.018	.007	2
HR3627	K0III	...	...	.020	.010	.025	.012	2
HR3664	G6III	...	...	.023	.017	.005	.017	2
HR3705*	M0III	3.13	3.74	.023	.005	.097	.005	7
HR3731	K2III	4.46	2.78	.019	.009	.060	.009	2
HR3748	K4III	1.97	3.16	.026	.004	.088	.004	4
HR3773	K5III	4.31	3.69	.024	.007	.093	.007	2
HR3800	G8III	4.55	...	.011	.007	.021	.006	2
HR3845	K3III	3.91	3.01	.021	.007	.071	.006	2
HR3888	F2IV	3.81	.81	-.002	.024	-.003	.020	1
HR3905	K2III	3.88	2.66	.024	.003	.069	.004	5
HR3950	M2III	4.70	4.20	.028	.002	.110	.002	7
HR3980	K4III	4.37	3.33	.042	.015	.090	.015	1
HR4008	M0III	...	...	.025	.001	.109	.002	3

TABLE 1-continued

Star	Spectral Type	V	V-K	[2.1 μ]-[2.2 μ] Index	1σ Error	[2.3 μ]-[2.2 μ] Index	1σ Error	No. Observations
HR4044	K1III	...	...	.023	± .005	.067	± .005	3
HR4069*	M0III	3.05	3.93	.030	.001	.108	.001	14
HR4094	K4III	3.79	3.42	.022	.008	.104	.009	2
HR4232	K2III	3.11	2.83	.031	.010	.084	.010	2
HR4267	M5III	...	...	.050	.011	.120	.011	2
HR4278	M2III	6.00	...	.040	.008	.123	.004	2
HR4301	K0III	1.79	2.44	.013	.006	.056	.006	2
HR4335	K1III	3.01	2.57	.036	.031	.069	.032	2
HR4336	M2III	...	...	.037	.011	.108	.012	2
HR4434	M0III	3.85	3.99	.024	.005	.110	.004	2
HR4517	M1III	4.04	3.96	.036	.008	.115	.007	2
HR4518	K0III	3.72	2.77	.025	.009	.066	.006	2
HR4608*	G8III	4.12	2.22	.022	.006	.034	.005	4
HR4666	M1III	...	...	.017	.018	.092	.018	1
HR4667	K0III	...	...	.029	.009	.026	.006	2
HR4690	M1III	...	...	.009	.015	.117	.010	2
HR4695	K1III	4.96	2.77	.025	.008	.079	.007	2
HR4697	G8III	4.74	...	.024	.003	.038	.002	6
HR4699	K1III	...	...	.024	.025	.033	.028	1
HR4716	G7III	4.80	...	.012	.009	.020	.009	2
HR4725	K0III	6.03	...	.014	.011	.038	.008	2
HR4741	G8III	...	...	.015	.031	.036	.028	1
HR4779	G8III	...	...	-.027	.013	-.017	.019	1
HR4783	K0III	...	...	.010	.012	.057	.012	2
HR4784	K1III	...	...	.002	.023	.034	.015	2
HR4786	G5III	2.64	1.94	.029	.008	.036	.006	2
HR4792	K2III	...	...	.014	.008	.034	.008	2
HR4812	K1III	...	...	-.019	.021	.025	.030	1
HR4813	K2III	4.67	...	.035	.013	.061	.013	1
HR4837	G8IIIP	5.93	...	.028	.020	-.001	.024	1
HR4902	M3III	4.80	4.67	.033	.005	.125	.005	2
HR4910	M3III	3.38	4.63	.027	.002	.072	.001	8
HR4932	G9II-III	2.84	2.04	.024	.003	.021	.003	1
HR4949	M5III	5.60	5.83	.048	.009	.130	.011	2
HR5020	G8III	3.00	2.02	.019	.005	.036	.006	3
HR5270	G0IV	...	...	-.016	.007	.013	.004	1
HR5340	K2IIIP	-.05	2.95	.021	.001	.079	.001	14
HR5370	K3III	4.86	...	.035	.010	.059	.010	2
HR5429*	K3III	3.59	2.93	.024	.001	.081	.001	10
HR5430	K4III	4.25	...	.020	.007	.048	.006	1
HR5502	K0III	4.60	2.17	.027	.009	.029	.008	2
HR5563	K4III	2.08	...	.032	.011	.101	.013	2
HR5602	G8III	3.50	2.16	.022	.007	.033	.008	3
HR5603	M4III	3.27	4.67	.063	.008	.116	.009	2
HR5681	G8III	3.49	2.27	.023	.008	.028	.009	3
HR5744	K2III	3.29	2.61	.028	.007	.059	.007	3
HR5854	K2III	2.64	2.58	.025	.004	.058	.003	4
HR5879	M1III	4.09	4.06	.026	.008	.118	.006	2
HR6056	M1III	2.75	3.97	.024	.006	.108	.004	5
HR6075	G9III	3.23	2.24	.018	.008	.039	.005	2
HR6134	M1-M2IAB	.91	4.69	.042	.005	.163	.005	2
HR6146	M6III	5.01	7.02	.049	.005	.129	.008	3
HR6299	K2III	3.20	2.56	.022	.007	.070	.007	3
HR6337	M3III	4.98	4.46	.021	.006	.119	.007	3
HR6406	M5II+G5II	3.06	6.57	.045	.002	.143	.002	7
HR6603	K2III	2.77	2.54	.026	.005	.067	.006	3
HR6688	K2III	3.75	2.72	.012	.006	.061	.008	3
HR6705	K5III	2.22	3.56	.029	.006	.102	.005	3
HR7009	M4-5I-IIB	...	...	.041	.009	.157	.009	2
HR7139	M4II	4.30	5.53	.034	.008	.146	.010	2
HR7157	M5III	4.00	6.09	.031	.015	.143	.013	2
HR7429	K3III	4.45	2.69	.035	.008	.055	.006	1
HR7576	K3III	...	...	.034	.013	.073	.014	1
HR7941	M5II-III	...	...	.074	.002	.151	.002	1
YUMA	M7II-III	...	...	.095	.005	.148	.004	2
SWVIR	M7III	...	...	.060	.005	.136	.004	2
RTVIR	M8III	...	...	.124	.006	.143	.006	2
BKVIR	M7III	...	...	.096	.010	.137	.011	2
RXBCO	M8III	...	...	.114	.001	.138	.001	1
Y49B †	M6V	11.03	5.21	.168	.027	-.018	.019	1
Y1305	DM5	11.48	4.95	.123	.023	-.037	.018	1
Y1609	DM3	9.99	4.38	.079	.008	-.010	.007	2
Y1668 †	DM6	11.49	5.63	.181	.020	.021	.018	1
Y1755	DM5	9.82	4.99	.092	.009	-.026	.008	1
Y2553	DM8	13.53	...	.135	.021	-.037	.014	1
Y4607	K0V	4.69	1.83	.013	.005	-.013	.005	1
Y5077A	K5V	5.23	2.82	.058	.008	-.056	.004	2
Y5077B	K7V	6.02	3.28	.012	.003	-.020	.003	1
Y5616	K3V	5.57	2.29	.017	.017	-.058	.018	1

* Standard stars

† Stars not included in figures 3 and 4

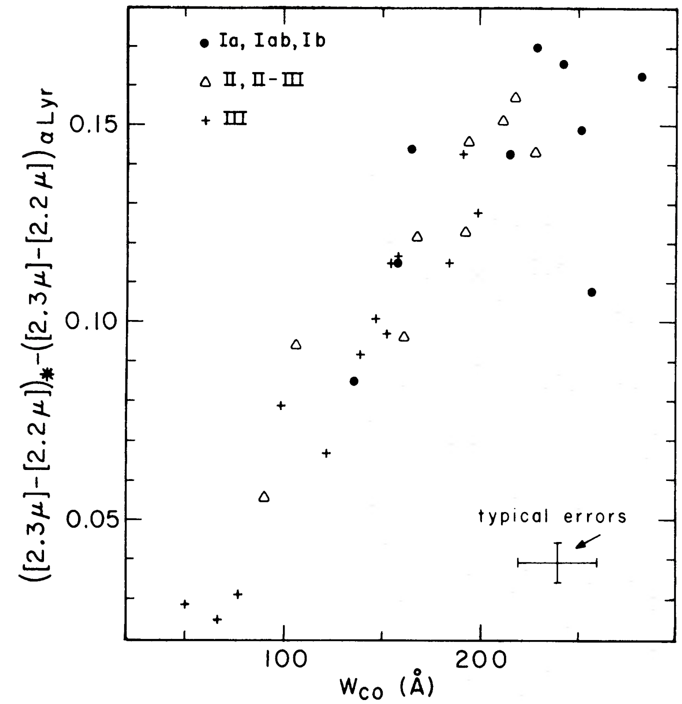

FIG. 2.—Equivalent width of the absorption from the (2, 0) to the (5, 3) band head of the first overtone band of $^{12}C^{16}O$ is compared with the [2.3 μ] − [2.2 μ] index.

Furthermore, examination of medium-resolution spectra of 70 stars in the region from 2.0 to 2.4 μ (Frogel 1971) revealed no atomic or molecular absorption features whose strengths are at all comparable with those of CO and H_2O. Since the range in luminosity and spectral type spanned by the spectroscopic survey is virtually identical to that covered in the present work, we proceed on the assumption that the intermediate-band system responds primarily to the absorption strengths of CO and H_2O. Except for the dwarfs, as discussed below, the slope of the stellar continuum does not significantly affect the indices.

Figures 3 and 4 show the two observed indices as functions of spectral type. The dashed lines in both figures represent the predicted dispersion computed from the errors in the individual observations of luminosity class III stars. The agreement between the observed and predicted dispersion for these stars indicates that the observed dispersion is due solely to observational uncertainties.

Several trends stand out in figure 3. The CO index increases with increasing luminosity. The giant and supergiant sequences are parallel, with a separation of about 0.04 in the index. The division between the dwarfs and giants for spectral types later than K0 is most pronounced. The CO index increases strongly with decreasing temperature in the giants and supergiants.

The appearance of CO absorption in the spectra of late-type stars has been discussed by many authors and reviewed by Spinrad and Wing (1969). Frogel (1971) discusses mechanisms that could account for the kind of variation in the CO absorption described above. There are four parameters that can affect the integrated band intensities: the temperature, pressure, column density of CO, and the microturbulent velocity of the gas. Calculations by V. G. Kunde (personal communication) have shown that changes of ~ 5 km s^{-1} in the microturbulent velocity can produce large changes in the strength of the CO absorption bands. These changes are considerably

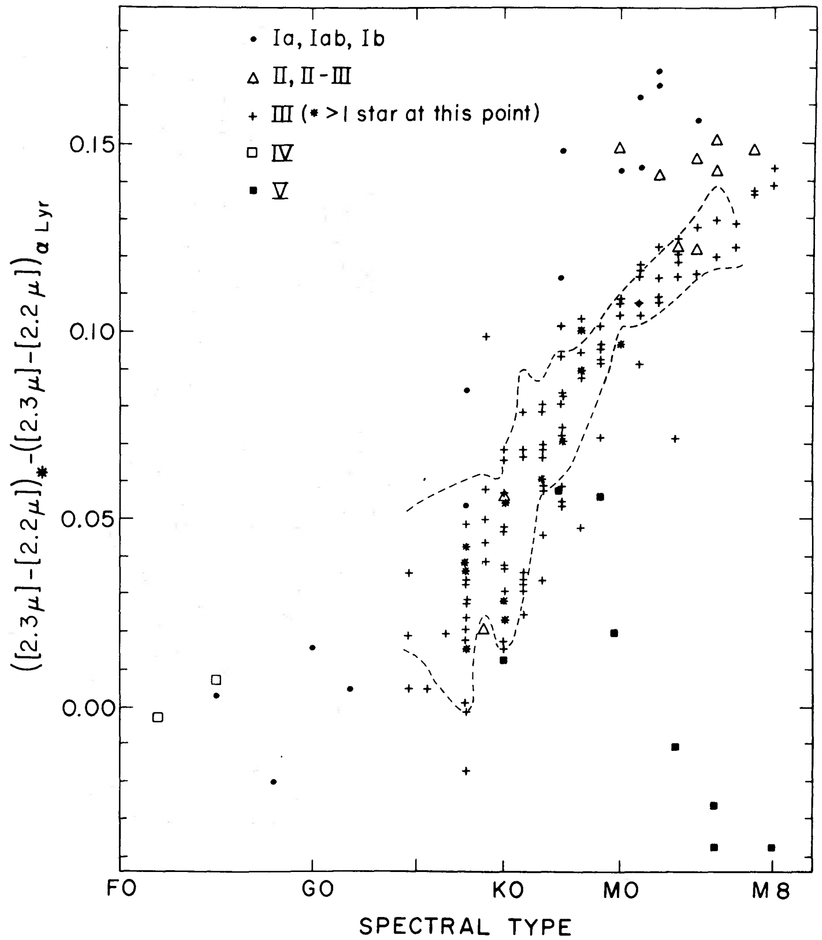

FIG. 3.—The mean relations between CO index, referred to α Lyrae, and spectral type for stars of luminosity classes I–V. Dashed lines represent the dispersions in CO index for class III stars, and are consistent with the 1 σ errors of observation of a single star.

greater than any change produced by reasonable variations in any of the other parameters including CO abundance. An increase in microturbulence with decreasing temperature among the giants and supergiants, and a similar increase with increasing luminosity from dwarfs to supergiants, could then account for the observed variation of CO absorption. This effect would be strongest if the bands were saturated.

A systematic increase in line blanketing with increasing luminosity and advancing spectral type may also affect the observed photometric indices. Model stellar-atmosphere analyses (Mihalas 1970) have shown that extensive line absorption results in a lowering of the boundary temperature relative to an unblanketed model. Moreover, the associated backwarming effect redistributes the flux blocked by the lines into the neighboring continuum. Both of these effects conspire to produce a line whose core is darker, relative to the continuum, than would be expected if the processes of line and continuum formation were decoupled. An accurate assessment of the influence of line blanketing on the present observations cannot be made until more detailed infrared spectra and reliable model atmospheres become available for very late-type stars.

A final comment on the relation between the CO index and spectral type concerns

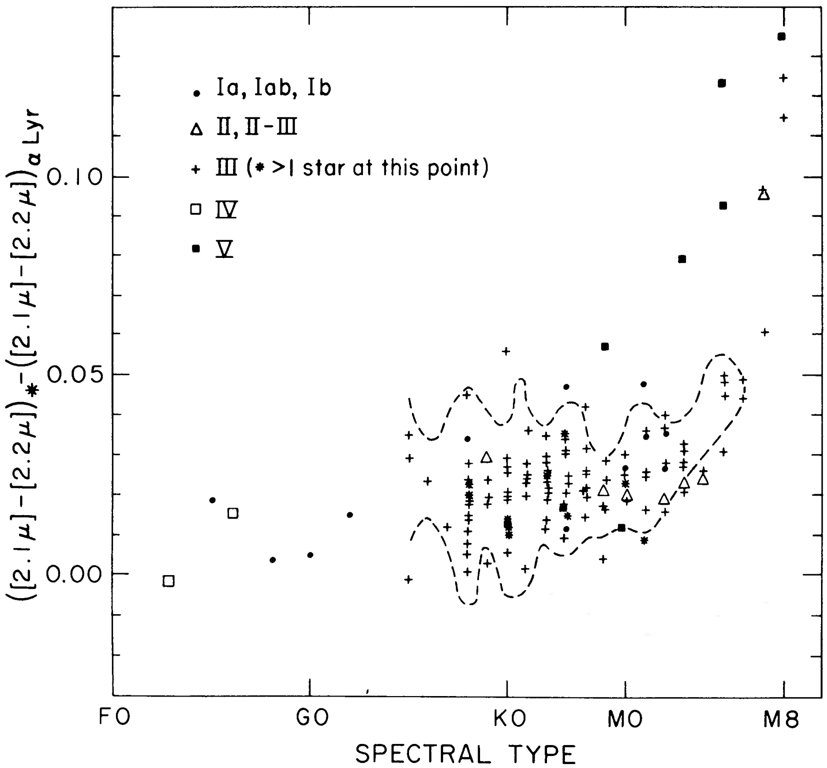

FIG. 4.—The mean relations between H_2O index, referred to α Lyrae, and spectral type for stars of luminosity classes I–V. Dashed lines represent the dispersions in H_2O index for class III stars through spectral type M6, and are consistent with the 1 σ errors of observation of a single star.

the apparently anomalous behavior of $[2.3\ \mu] - [2.2\ \mu]$ in dwarfs later than type K0. This decrease in CO index with decreasing temperature is not due to the absence of CO in dwarfs; rather, it reflects a flattening of the continuum in the 2.2-μ region as shown by the medium-resolution spectra (Frogel 1971).

The sensitivity of the $[2.3\ \mu] - [2.2\ \mu]$ index to luminosity and temperature suggests its use in conjunction with broad-band infrared photometry, as a classification parameter for late-type stars. In particular, the marked distinction between late-type giants and dwarfs with regard to both indices has been applied to a study of stellar populations in galaxies (Baldwin *et al.* 1973).

The increased strength of the H_2O index in the spectra of dwarfs with respect to that in stars of higher luminosity is clearly visible in figure 4, which shows the $[2.1\ \mu] - [2.2\ \mu]$ color as a function of spectral type. This is due both to the appearance of the 1.87-μ H_2O band at an earlier spectral type in dwarfs than in giants, and to the flatness of the dwarf continuum relative to that of giants.

For giants and supergiants earlier than M6, the H_2O index is relatively constant. The spectra of stars of these types observed in common with Frogel (1971) showed no absorption due to the 1.87-μ band of H_2O. Thus, apparently none of these stars observed in the present study has noticeable H_2O absorption in this spectral region. A similar conclusion for this and other spectral regions was reached by Johnson *et al.* (1968), Johnson and Mendez (1970), and Spinrad and Wing (1969). The sudden upturn of the H_2O index in small-amplitude irregular variables of types M7 III and M8 III is compatible with the data of Frogel (1971) and the 1-μ observations of Spinrad and Newburn (1965).

IV. SUMMARY

We have shown that a photometric system, consisting of three intermediate-band filters in the 2.2-μ spectral region, can serve as an indicator of the absorption strengths of the first overtone band of CO near 2.3 μ and the 2.1-μ wing of the 1.87-μ H_2O absorption. We find no evidence to within the observational errors for a dispersion in the CO or H_2O band strengths of luminosity class III stars. The CO index increases with increasing luminosity and, in giants and supergiants, with decreasing temperature. The photometric system is useful for identifying and classifying late-type stars, and has been used for obtaining information on the stellar content of galaxies (Baldwin *et al.* 1973). The H_2O index is small and relatively constant for giants and supergiants between spectral types F2 and M6. It is substantially larger in small-amplitude irregular variables of types M7 III and M8 III and in late-type dwarfs.

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