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INFRARED SPECTROSCOPY OF M DWARFS

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ABSTRACT

High-resolution Fourier transform spectra are presented for six M dwarfs. The wavelength range is 4000–6600 cm^{-1} at 0.3 cm^{-1} resolution. Abundance analysis indicates that the old disk subdwarfs Gliese 15 A and 411 are metal-poor ([M/H] = −0.35), while Gliese 205, which lies above the main sequence in the HR diagram, is metal-rich ([M/H] = 0.5). This correlation between luminosity and metallicity is used to obtain an upper limit to the abundance dispersion in M dwarfs of the disk population. The similarity between this result and that obtained for G dwarfs suggests a common history of chemical enrichment for these stars.

Subject headings: infrared: spectra — stars: abundances — stars: late-type — stars: subdwarfs

I. INTRODUCTION

The large dispersion in the HR diagram of nearby M dwarfs was recently rediscussed by Mould and Hyland (1976). From a study of molecular band strengths and from infrared photometry, they concluded that both abundance and age effects were responsible for this dispersion. Subdwarfs were found, both in the halo and the disk populations (Mould and McElroy 1978), to be metal-poor, and a number of stars forming an upper envelope to the main sequence were argued to be still in the phase of gravitational contraction.

The availability of a high-resolution Fourier transform spectrometer (FTS) at the Kitt Peak 4 m telescope suggested that spectroscopy of M dwarfs might also usefully be extended to the infrared in order to test and further develop this picture of the lower main sequence. In this paper spectra of a sample of six M dwarfs are presented (§ II). Together they cover the full spread in the HR diagram of the disk main sequence. Analysis of line strengths is carried out in § III, and the implications concerning the spread of the main sequence are discussed in §§ IV and V.

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II. OBSERVATIONS

Infrared spectra of six M dwarfs were obtained with a prototype 10 cm FTS (Hall 1977; Ridgway and Capps 1974) at the Mayall 4 m telescope during the period 1977 January–October. The photometric properties of the program stars are given in Table 1, where the stars are identified by their numbers in the Gliese (1969) catalog. Infrared photometry is taken from Mould and Hyland (1976) and Veeder (1974). The temperatures in Table 1 are from the calibration of 1 $\mu\Delta$ by Mould and Hyland. A zero-point correction of +0.035 mag is required to put new measurements of 1 $\mu\Delta$ (Mould and McElroy 1978 and unpublished) on the old scale. A small zero-point correction has also been made to Veeder's bolometric magnitudes. In the K magnitude range of Table 1 integrations of 1–3 hours were required in order to produce spectra with a signal-to-rms-noise ratio greater than 15 at an apodized resolution of 0.3 cm^{-1}. Barnard's star, Gl 699, was observed at a lower resolution (0.5 cm^{-1}). The useful wavelength range of the present spectra is 4000–6600 cm^{-1}, but the signal-to-noise ratio beyond 6000 cm^{-1} is considerably reduced.

Portions of typical spectra are shown in Figure 1, which also demonstrates the technique for removing terrestrial lines. The program spectra were divided by

TABLE 1

PHOTOMETRIC PROPERTIES OF THE PROGRAM STARS

Gliese	Name	Sp. Type*	V	K	1 $\mu\Delta$†	log T_e	M_{bol}
15 A.........	HD 1326 A	M1 V	8.07	4.03	0.60	3.532	8.97
205..........	HD 36395	M1 V	7.98	3.86	0.515	3.560	7.56
229..........	HD 42581	M1 V	8.14	4.24	0.52	3.558	7.93
411..........	HD 95735	M2 V	7.49	3.38	0.59	3.535	8.97
699..........	Barnard's star	M5 V	9.54	4.50	0.825	3.475	10.86
820 B........	61 Cyg B	K7 V	6.03	2.71	0.42	3.596	7.47

* From Gliese 1969.
† 1 $\mu\Delta$ = m(7540) − m(10175) on the F_ν scale of Hayes and Latham 1975.

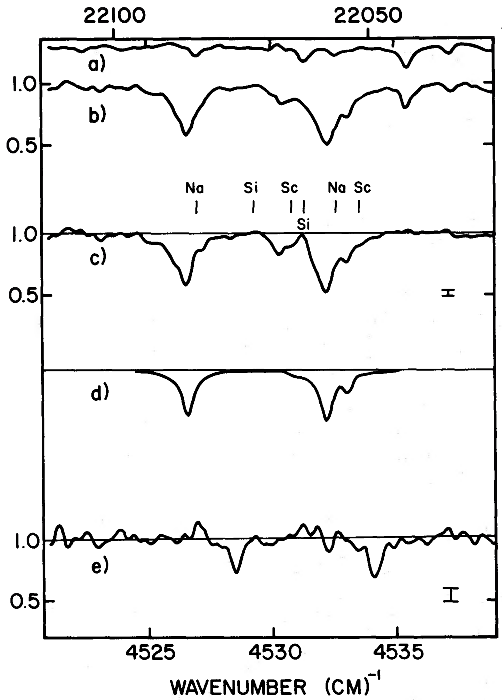

FIG. 1.—Typical spectra in the range 4520–4540 cm^{-1}: (*a*) α CMi, offset vertically by +0.3 divisions (note the presence at ~zero velocity of weak Na lines and an Si line); (*b*) Gl 205 (slight redshift); (*c*) Gl 205 ratioed to α CMi; (*d*) a synthetic spectrum at 3500 K and solar abundance; (*e*) Gl 411 (~2 cm^{-1} blueshift) ratioed to α CMi. The signal-to-noise ratio derived from the rms deviation of the forward and reverse scans is shown as a 2 σ error bar. A wavelength scale in angstroms is given above.

high signal-to-noise spectra of early-type stars scaled to the same air mass. The stars α Lyr and α CMi were used for this purpose, although the latter has the disadvantage of contamination by weak high-excitation stellar lines. The apodizing function used with these spectra was of the form $[1 - (x/L)^2]^2$.

No loss of spectrophotometric information occurs in Fourier transform spectroscopy, and this is exploited in Figure 2, where energy distributions of four of the program stars are presented. Here the data have been transformed to 5 cm^{-1} resolution, following Mould *et al.* (1978). The prominent features of the spectra at this resolution are the first-overtone CO band heads, several 3–5 volt excitation lines of neutral light elements, and the 1.9 μm band of water vapor strengthening with decreasing temperature. This is seen first as a flattening of the continuum and finally as a deep depression in the spectrum of Gl 699.

III. ANALYSIS OF THE SPECTRA

a) *Strong Atomic Lines*

Between 4500 K and the effective temperature range represented here, atoms of the abundant elements of low ionization potential (excepting Na) finally become neutral in dwarf atmospheres. This accounts for the great enhancement over the solar photospheric spectrum of the atomic lines identified in Figure 2.

The strengths of these lines are readily measured from 0.3 cm^{-1} spectra (e.g., Fig. 1). We have omitted those lines (e.g., the Ca lines near 5050 cm^{-1}) for which the continuum in Gl 15 A is depressed by water vapor by more than 5%. Equivalent widths of the remaining lines, measured with a simple trapezoidal integration scheme, are recorded in Table 2. Maximum errors are estimated at 15%. Care was taken to account for the effects of pseudoemission lines in ratioed spectra (see Fig. 1). It is useful to recall when examining these numbers that the dimensionless equivalent width W_σ/σ is equal to W_λ/λ. Thus a line of 100 mK[1] at 5000 cm^{-1}

[1] 1 milli-Kayser = 10^{-3} cm^{-1}.

TABLE 2

EQUIVALENT WIDTHS IN mK

σ (cm^{-1})	Gl 411	Gl 205	Gl 229	Gl 15 A	Gl 820 B	Gl 699	log *gf*
Na 4276.15	130	305	275	225	230	150	+0.63
Na 4281.77	90	240	165	125	150	60	+0.38
Ca 4413.55	145	340	220	175	230	55	+0.46
Ca 4418.69	95	320	245	135	215	35	+0.20
Ca 4422.02	110	195	130	90	130	25	−0.42
Na 4526.99	170	540	350	175	230	155	−0.27
Na 4532.59	305	660	475	240	380	195	+0.04
Ti 4454.03	< 25	50	50	45	25	45	−2.03
Ti 4480.95	30	60	45	35	25	80	−1.91
Ti 4488.30	30	120	70	45	30	30	−1.54
Ti 4496.61	60	105	45	65	50	30	−1.44
Ti 4501.00	45	95	45	45	55	35	−1.55
Ti 4543.28	45	85	85	55	40	< 20	−1.66
Ti 4565.51	80	95	115	...	80	55	−1.23
Ti 4589.50	100	150	105	85	90	95	−0.94
Mg 5843.39	435	890	740	360	925	...	+0.24
Al 5963.77	185	370	275	190	305	< 60	−0.40
Al 5968.4	445	905	820	530	685	195	+0.55
Al 5979.6	260	670	555	240	535	245	+0.29
Fe 6124.08	20:	90	...	...	90:	...	−0.16
Fe 6300.04	< 20:	100	...	...	70:	...	+0.00
Fe 6399.68	105:	175	...	...	205:	...	+0.40

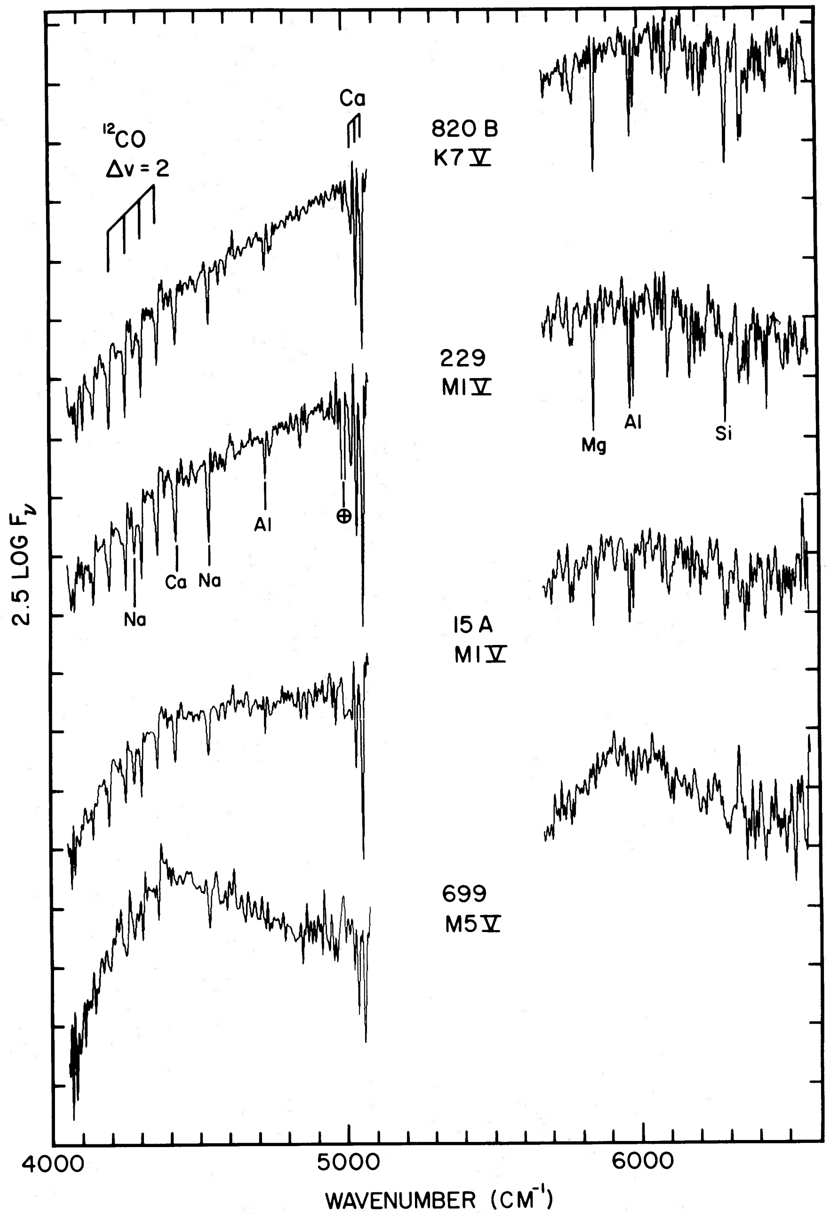

FIG. 2.—Spectrophotometry of four of the program stars. Vertical ticks are separated by 0.1 mag. The data have been masked out in the opaque region 5080–5670 cm^{-1}. The first four heads of the first-overtone band of ^{12}CO are identified, together with a number of strong neutral metal lines. The terrestrial CO_2 band ⊕ near 5000 cm^{-1} has not been fully corrected out in the spectrum of Gl 229 (air mass 1.7).

has equivalent strength to a line of 100 mÅ at 5000 Å.

For compactness we have plotted in Figure 3 the mean equivalent width versus stellar temperature for adjacent lines of the same multiplet. Also shown (*top left*) are the positions of the individual stars in the HR diagram. The correspondence between the line strength-temperature diagrams and the luminosity-temperature diagram is the really striking feature of Figure 3. Relative to the mean main-sequence line established by Mould and Hyland (1976), the overluminous star Gl 205 is strong lined, and the subdwarfs Gl 411 and 15 A are weak lined. The natural interpretation is that metallicity differences underlie this correlation.

Quantitative analysis of these line strengths was carried out by using a spectrum synthesis program written by R. L. Kurucz, together with Mould's (1976*a*) grid of models for M dwarf atmospheres. The *gf*-values for the lines were obtained by iterating on those of Kurucz and Peytremann (1975) in order to match the photospheric line strengths in Hall's (1974) atlas. Departures from the original values of log *gf* were less than 0.3 in all cases (see Table 2). Some details

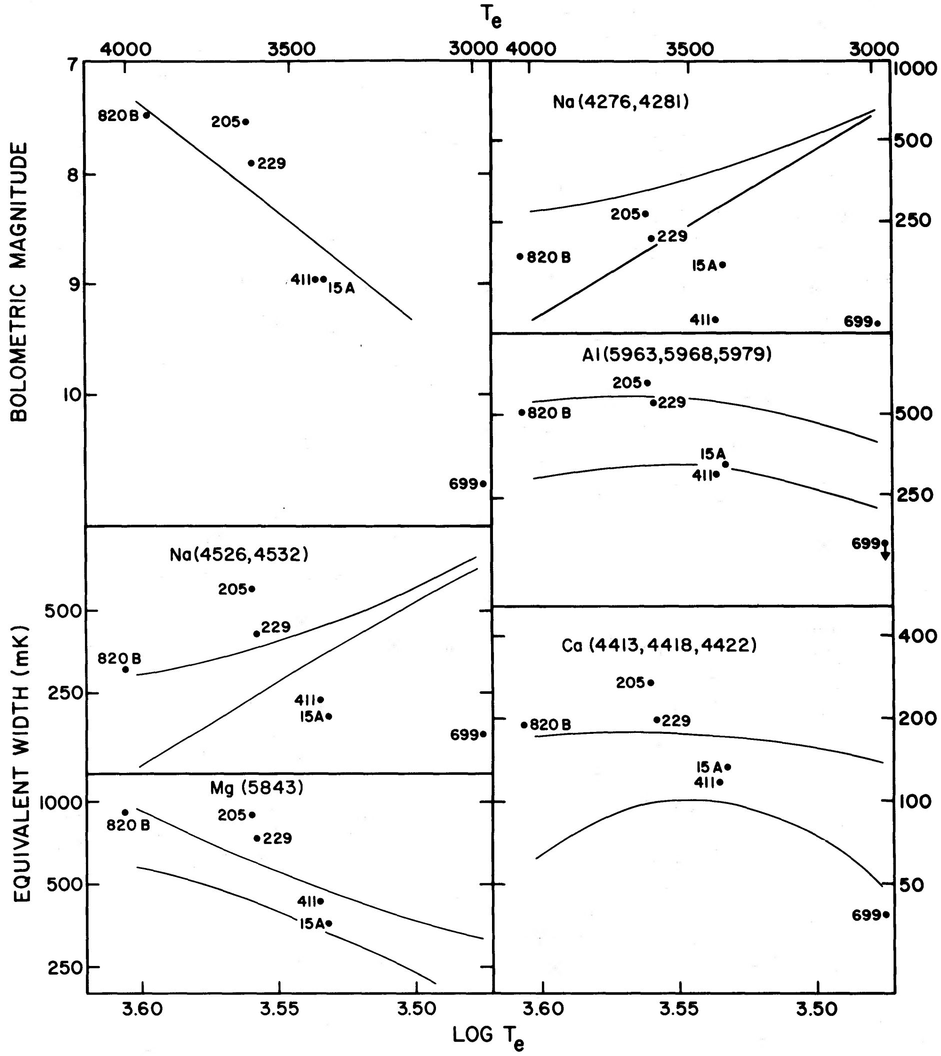

FIG. 3.—The program stars are shown in the HR diagram (*top left*). The line represents the mean old disk main sequence. Probable errors in the relative magnitudes are less than 0.05 and in the relative temperatures are 0.005 dex. In the other panels, mean equivalent widths of the indicated lines are shown as a function of temperature. Theoretical loci of mean equivalent width versus temperature are shown for two compositions: solar (*upper curves*) and one-fifth solar (*lower curves*). The diagram indicates the connection between main-sequence position and metallicity.

of the synthesis program and in particular the adopted intrinsic line-broadening treatment are given by Mould (1978). For comparison with FTS data the spectra were extrinsically broadened by the apodized instrumental profile, yielding line profiles similar to those in Figure 1*c*. Equivalent widths were then measured with the same technique used for the empirical data.

The results are shown in Figure 3 as a pair of theoretical curves for solar abundance (Lambert 1976) and one-fifth solar abundance (*lower curves*). These loci were generated from three pairs of models at 4000 K, 3500 K, and 3000 K effective temperature with $\log g = 4.75$. An additional model (3750 K) with 1/100 solar abundance confirms the steady metallicity dependence of these lines. A further model (3500 K) with $\log g = 5.75$ establishes very little gravity sensitivity in these lines, with the exception that the Na lines increase in mean line strength by a factor of 1.7. This and the other exceptional property of the Na lines, their steady increase with decreasing temperature, result from the fact that Ne remains ionized throughout the temperature range of these atmospheres.

In general, the predicted curves in Figure 3 for solar composition pass through or close to Gl 229 and 820 B (61 Cyg B). The Na (4276, 4281) lines could be brought into agreement with this picture by a reduction in the damping constant of a factor of 2. If we discount all the Na lines (*a*) because they are neutral lines of an ionized element and (*b*) because it seems impossible to fit Gl 699 at any abundance, it appears that the subdwarfs Gl 15 A and 411 lie between the two composition loci, but closer to one-fifth solar abundance.

The formal results relative to solar composition are [M/H] = 0.0 for Gl 820 B, 0.45 for Gl 205, 0.15 for

Gl 229, and −0.5 for Gl 15 A and 411. The combined errors suggest an uncertainty of ±0.15 dex. We stress the relative abundances rather than the absolute results which are dependent on the calculated damping constants. The case of Gl 699 is difficult, as it is so much cooler than the other stars. The results suggest [M/H] < −0.7, but may be deceptive, as none of the continua can be guaranteed to be uncontaminated by H_2O absorption.

b) *Weak Atomic Lines*

A number of weak lines of the iron peak elements are also visible in the 0.3 cm^{-1} resolution spectra. Most easily measured are a group of 1.74 eV Ti lines near 4500 cm^{-1}. Equivalent widths are recorded in Table 2. Given the noise, these are more uncertain than the strong line entries. While the measurements are straightforward, these low-excitation Ti lines are hard to interpret because of the effects of TiO depletion on the neutral Ti. This matter has been discussed in detail by Mould (1976*b*): however, the effects are visible in calculated curves of growth drawn in Figure 4*a*. Ti depletion conspires to merge the curves of growth for different temperatures at solar abundance, but lesser depletion at [M/H] = −0.7 separates them again. The result is reduced abundance sensitivity at lower temperatures.

Empirical *gf*-values are not available for these lines, which are invisible in the photospheric spectrum. However, if we take the warmest program star (negligible Ti depletion) and construct a curve of growth with theoretical *gf*-values (Kurucz and Peytremann 1975), the result is quite satisfactory. A zero-point shift of +0.3 dex to the theoretical values allows a 4000 K calculated curve of growth to fit the equivalent widths of Gl 820 B rather well at solar abundance (Fig. 4*a*). For this and the other program stars, a microturbulent velocity of 2 km s^{-1} was adopted. With this zero-point shift subsequent Ti abundances are relative to Gl 820 B.

Figures 4*b* and 4*c* show clearly that Gl 15 A and 411 are weak lined relative to Gl 229 and 205. Given the complex abundance sensitivity of Ti, quantitative interpretation is hazardous. However, with the aid of the calculated curves of growth, we obtain [Ti/H] = 0.75 for Gl 205, 0.15 for Gl 411, 0.55 for Gl 229, and 0.25 for Gl 15 A, all relative to Gl 820 B. Abundance analysis of Gl 820 B with respect to the Sun has been carried out by Oinas (1974). He obtained [Ti/H] = −0.6. This star was the coolest in his program, however, and the program met with considerable difficulties in the ionization equilibrium. Oinas's result contrasts with the analysis of Gl 820 A (K5 V) by Strohbach (1970), who obtained [M/H] = 0.0 ± 0.3. According to Eggen (1978*a*), the 61 Cyg group as a whole has [M/H] = −0.35. For the present we must consider the whole analysis of Ti lines very uncertain, but adopt for Gl 820 B [Ti/H] = −0.3 ± 0.3 to correct the above values to solar composition.

Easier to interpret, but correspondingly harder to measure, are the many high-excitation (5–6 eV) lines of Fe in the 5900–6500 cm^{-1} region. Uncertain excitation estimates and noisy spectra have restricted useful measurements to three lines from the list of Biémont (1976) in three stars. For these lines, *gf*-values were obtained from a match to the solar spectrum. From the measurements in Table 2 and line strengths calculated for the grid of models we obtain relative to the Sun, [Fe/H] = 0.6 ± 0.2 for Gl 205, −0.2 ± 0.3 for Gl 411, and 0.0 ± 0.2 for Gl 820 B. The uncertainties

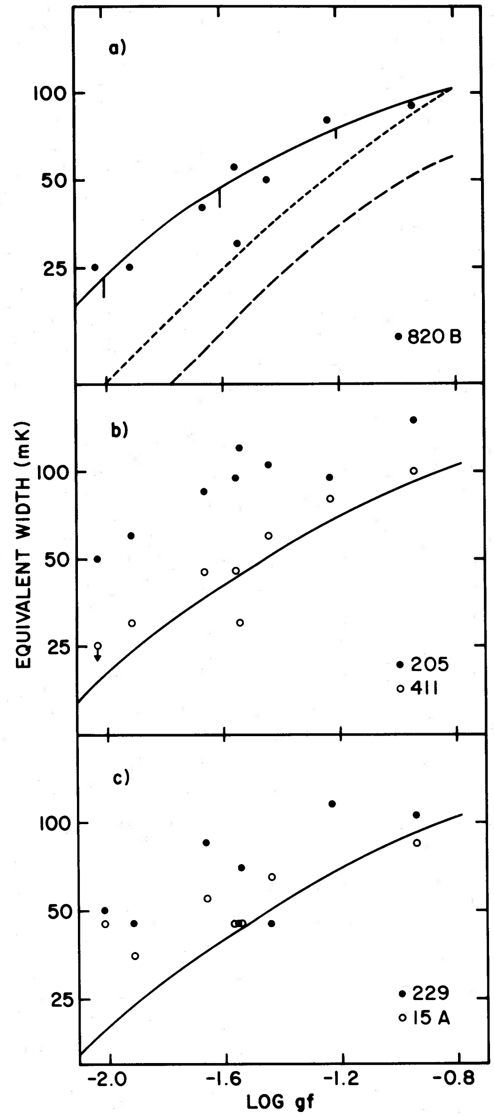

FIG. 4.—The abundance analysis for the Ti lines. (*a*) Gl 820 B is taken as the standard, and a 4000 K solar abundance curve of growth is fitted (*solid line*). The vertical bars indicate the change in the calculated curve for 3500 K effective temperature. The other two lines are for 4000 K, [M/H] = −0.7 (*long dashes*) and 3500 K, [M/H] = −0.7 (*short dashes*). In (*b*) and (*c*) the displacement of the curves of growth defined by the remaining program stars from the 3500 K standard abundance line (*solid lines*), relative to the theoretical displacements in (*a*), measures abundances with respect to Gl 820 B.

arise from estimated relative temperature errors and equivalent-width measurements. In addition, for these 5.5 eV lines there is a systematic uncertainty of ± 0.15 dex from the absolute temperature scale for M dwarfs (Mould and Hyland 1976).

c) *Molecular Lines*

In all the program stars at 0.3 cm^{-1} resolution, rotational lines of the first-overtone bands of CO and OH are clearly visible. Below 3500 K it is possible to identify numerous rotational lines of H_2O from wavelengths tabulated by Hall (1974) and Benedict (unpublished). A search for the quadrupole vibration-rotation lines of H_2 at the wavelengths given by Spinrad and Wing (1969) proved negative. Nondetection is consistent with Spinrad's (1966) line strength–column density relation, however. In addition, neither lines nor band heads of ^{13}CO were detected. This would be consistent with the terrestrial abundance ratio, of course. A determination of $^{12}C/^{13}C$ for these old main-sequence stars would be valuable, but must await spectra of higher resolution and signal-to-noise ratio.

In Table 3 are recorded the mean equivalent widths of a number of CO and OH lines which are suitably placed for accurate measurement. Synthetic spectra of these lines have been calculated from theoretical *gf*-values by Kirby-Docken and Liu (1978) and Mies (1974). Mies's values have been scaled to agree with the integrated absorption coefficient of Benedict and Plyler (1954). The solar abundances of C, N, O were taken from Lambert (1978).

In the case of OH a rather clear-cut abundance sensitivity is predicted. Yet the OH line strengths in Gl 15 A and 411 are no weaker than in Gl 205 and 229. We suggest that in these old disk subdwarfs oxygen is *not* underabundant to the extent of the other metals. Given the metallicity of Gl 15 A and 411 derived above, [O/C] = 0.15 would seem to be required.

A rather lower abundance sensitivity is predicted for CO. The almost complete association of CO in cool dwarfs means that the number density of CO will vary with C rather than with the product of C and O. The observations (Table 3) seem consistent with the hypothesis that [C/Fe] = 0 in these stars.

TABLE 3

EQUIVALENT WIDTHS (mK) OF CO AND OH LINES

	CO	OH
Gliese		
15 A	50	55
205	70	40
229	65	55
411	60	50
699	55	...
820 B	75	40
Model		
4000 K, [M/H] = 0	60	30
3500 K, [M/H] = 0	70	40
4000 K, [M/H] = −0.7	35	15
3500 K, [M/H] = −0.7	50	25
3500 K, [M/H] = −0.7*	50	50
3500 K, [M/H] = 0†	55	20

NOTE.—CO is the mean of 14 lines designated OR 20–23; OH is the mean of four *P* (14) (3, 1) lines and four *P* (9), (4, 2) lines.

* [O/C] = 0.3.

† log *g* = 5.75.

IV. THE SPREAD OF THE MAIN SEQUENCE

The results of the preceding section are summarized in Table 4. Somewhat smaller abundance differences are apparent in Ti and Fe than in the lighter metals, but we cannot insist on the significance of this, given the uncertainties in the analysis. Instead, a mean value of [M/H] has been derived by double weighting the combined Al, Ca, and Mg abundance. No quantitative results have been obtained for Gl 699, because of the excessive H_2O blanketing. A considerable metal deficiency is suggested, however.

The present study clearly implies that the spread in the disk main sequence, at least among the early M dwarfs, is basically a metallicity spread. The sense of this spread is that metal-rich stars are overluminous with respect to metal-poor subdwarfs. In this respect infrared spectroscopy strongly reinforces the results of Mould and McElroy (1978), which were based on narrow-band photometry of molecular band strengths. This (CaH, TiO) photometry readily separates the halo and disk main sequences, but has only marginal sensitivity for the smaller abundance spread found in the disk.

Special attention should be drawn to the result for Gl 205. Space motions quoted by Woolley *et al.* (1970) suggest that Gl 205 is a probable member[2] of the HR 1614 group of overabundant stars (Eggen 1978*b*). However, Mould and Hyland (1976), basing their discussion of the lower main sequence on infrared photometry, considered Gl 205 (=Yale 1255) to be one of a number of overluminous stars still contracting to the main sequence. These stars were identified by their $J - H$ excess, considered to be a result of low gravity. The $J - H$ deficiency of subdwarfs, on the other hand, was held to be due to low metallicity.

[2] Eggen (private communication) has indicated that the group and trigonometric parallaxes for G1 205 are in exact agreement.

TABLE 4

SUMMARY OF ABUNDANCE DETERMINATIONS

Gliese	[M/H]*	[Ti/H]	[Fe/H]	Mean [M/H]
15 A	−0.5	−0.05	...	−0.35
205	+0.45	+0.45	0.6	+0.5
229	+0.15	+0.25	...	+0.2
411	−0.5	−0.15	−0.2	−0.35
820 B	0.0	−0.3	0.0	−0.1

* From Al, Ca, and Mg.

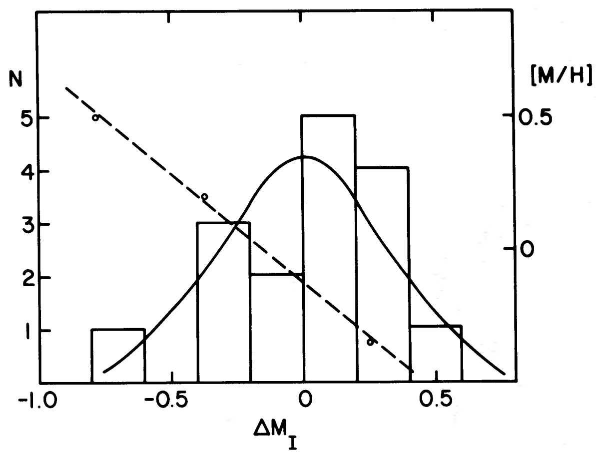

FIG. 5.—The frequency distribution of residuals ΔM_I from the ridge line of the (M_I, $R - I$) color-magnitude diagram. A Gaussian fit is shown. Superposed is the metallicity calibration (*dashed line*) of ΔM_I, derived from Gl 205, 229, and 411 (*open circles*).

Model-atmosphere predictions support the ambivalence of $J - H$ in this regard. Given the present (gravity-insensitive) result for Gl 205, insufficient attention seems to have been paid by Mould and Hyland to the possibility that some (or all?) of these overluminous stars with $J - H$ excesses are simply overabundant. Infrared spectra of some other of Mould and Hyland's contracting stars would appear to be required. However, since these stars are all cooler than Gl 205, the analysis will not be so straightforward.

A further desirable extension of the present work is to halo subdwarfs. Infrared spectra would permit a test of the TiO abundance calibration of Mould (1976*c*) together with a direct determination from OH and CO of the O/C ratio. There are no such stars accessible from the north, however, within 2 mag of the present observational limit. Kapteyn's star ($K = 5.0$) will require southern hemisphere observations.

V. THE ABUNDANCE DISPERSION FOR M DWARFS

Finally, we may use the present metallicity-luminosity correlation to obtain an upper limit to the abundance dispersion for M dwarfs of the disk population. For this purpose we consider a sample of old disk stars with reliable trigonometric parallaxes. To minimize other sources of dispersion the sample [Eggen's Table 1 (1973)], was restricted to (*a*) apparently single stars (visual and spectroscopic binaries excluded); (*b*) stars with probable errors in $m - M$ less than 0.15 mag in Woolley *et al.* (1970); and (*c*) the temperature range in which the present abundance determinations are concentrated [$0.75 < (R - I)_K < 1.05$]. The frequency distribution of residuals from a regression line in the (M_I, $R - I$)-plane is shown for this sample in Figure 5. The slope of the regression line was strengthened by extension of the sample to $R - I = 0.6$. The dispersion of a Gaussian fitted to this distribution is 0.33 in ΔM_I, which corresponds to 0.26 in [M/H]. Fortuitously, this coincides with an upper limit to the abundance dispersion for G dwarfs derived by Pagel and Patchett (1975).[3] However, the error in the Gaussian fit alone is ± 0.05 in [M/H]. Only three stars are available to calibrate ΔM_I against [M/H] (Gl 15 A is a spectroscopic binary), and no estimate can be made of the uncertainty of this calibration. Any (uncorrelated) dispersion in the helium abundance of the lower main sequence has been neglected.

The mean of the sample distribution corresponds to $[M/H] = -0.15$, compared with -0.36 for the G dwarfs. Given the probable (but uncorrelated) zero-point errors in each of the three methods of analysis in the preceding section, this difference may not be real.

The present quantitative upper limit supports the conclusions of Mould (1976*d*) from a preliminary test of the abundance dispersion in M dwarfs. This was based on a TiO abundance calibration which is less sensitive than the new spectroscopic criteria and which, in view of our estimate of [O/C] in subdwarfs, will require revision. More generally, the derived abundance dispersion clearly suggests a common history of chemical enrichment for the G dwarfs and M dwarfs of the disk population.

I would like to thank Don Hall and Steve Ridgway for their assistance throughout this project. I am also grateful to Robert Kurucz for the use of his spectrum synthesis program.

[3] Pagel and Patchett proceed to correct this dispersion down to a value corresponding to the dispersion due to enrichment alone. Without age resolution in M dwarfs it is impossible to follow this procedure. We note that the *observational* scatter in both G and M dwarf samples provides a very small (0.02–0.03) correction to the measured dispersion, so that the similarity between the two upper limits remains meaningful.

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