Calibrating M Dwarf Metallicities Using Molecular Indices

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ABSTRACT. We report progress in the calibration of a method to determine cool dwarf star metallicities using molecular band strength indices. The molecular band index to metallicity relation can be calibrated using chemical abundances calculated from atomic-line equivalent width measurements in high-resolution spectra. Building on previous work, we have measured Fe and Ti abundances in 32 additional M and K dwarf stars to extend the range of temperature and metallicity covered. A test of our analysis method using warm star–cool star binaries shows we can calculate reliable abundances for stars warmer than 3500 K. We have used abundance measurements for warmer binary or cluster companions to estimate abundances in six additional cool dwarfs. Adding stars measured in our previous work and others from the literature provides 76 stars with Fe abundance and CaH2 and TiO5 index measurements. The CaH2 molecular index is directly correlated with temperature. TiO5 depends on temperature and metallicity. Metallicity can be estimated to within ±0.3 dex within the bounds of our calibration, which extends from roughly [Fe/H] = +0.05 to −1.0, with a limited extension to −1.5.

1. INTRODUCTION

In Woolf & Wallerstein (2005) we reported the measurement of Fe and Ti abundances in 35 M and K dwarf stars using atomic-line equivalent width measurements from high-resolution (λ/Δλ ≈ 33,000) spectra. While the abundance survey provided useful results, it was clear that a method of estimating metallicity in cool dwarfs that works for fainter stars and that requires less analysis effort was needed. Although low-temperature dwarf stars are the most numerous stars in the Galaxy, their intrinsic faintness means that few of them are close enough to measure high-resolution spectra. Because the derived abundances depend on the metallicity of the model atmosphere, several iterations are required for each star before the model and derived abundances match.

Because low-temperature main-sequence stars, M dwarf and cooler, make up most of the baryonic mass of the Galaxy, we must know their chemical composition if we are to fully understand the chemical composition and evolution of the Galaxy. An open problem in modeling the chemical evolution of the Galactic disk is the “G dwarf problem”: fewer metal-poor G dwarfs are observed than models predict. The problem has been found to extend to stars with temperatures as cool as 4700 K (Flynn & Morell 1997). With a well-calibrated method to estimate M dwarf metallicities using low-resolution spectra, it will be possible to assemble a statistically significant sample of measurements and determine if the problem continues to stars with T = 3500 K or cooler.

Bonfils et al. (2005) combined abundances they measured in 20 binaries having M-dwarf secondaries and warmer primaries with the metallicity measurements from Woolf & Wallerstein (2005) to calibrate a M and V − K versus metallicity relation. Because the relation depends on absolute magnitude, it is useful only for stars that are close enough to measure accurate parallaxes.

In this paper we report a metallicity calibration using the CaH2 and TiO5 indices. CaH2 and TiO5 are molecular indices that measure CaH and TiO band strengths in cool dwarf stars (Reid et al. 1995). These can be measured with lower resolution (λ/Δλ ≈ 3000) flux-calibrated spectra and require only the measurement of relative flux levels in specified wavelength bands in spectra that have been corrected to zero velocity, which requires much less observational time and analysis effort than measuring and analyzing equivalent widths of atomic lines in higher resolution spectra. This method will allow metallicities to be estimated for stars at least 3 mag fainter and considerably more distant than can be observed at high resolution. With 4 m class telescopes, stars fainter than V = 16 can be observed with reasonable exposure times at this resolution. For a Mv = 10 star, this corresponds to a distance of about 160 pc, a distance greater than that for which reliable trigonometric parallaxes are available for large numbers of stars

We have measured abundances in additional cool dwarfs in order to extend the range of temperature and metallicity for which the metallicity relation can be calibrated. We have also used binaries with F, G, or K primaries and M dwarf secondaries to test our abundance analysis method and to extend the temperature and metallicity range.
off in the blue, normally around 5000 Å for M dwarfs, and using the echelle spectrograph of the Apache Point Observatory 3.5 m telescope. The spectral resolution is

Our first paper included few low-metallicity ([Fe/H] < −0.5) stars cooler than 3800 K, we obtained echelle spectra of additional M dwarfs with molecular band strengths that indicated they might have low metallicity.

To test the method we use to calculate abundances in M and K dwarfs, we observed a number of stars in binaries where one member is an F, G, or early K dwarf and the other is a K or M dwarf with a temperature in the range covered by our other stars. Most of these were selected from common proper motion pairs listed by Gould & Charnamé (2004). We also observed five Hyades M and K dwarfs.

We used the Dual Imaging Spectrograph (DIS) of the APO 3.5 m telescope to measure spectra of M and K dwarfs for which no TiO and CaH molecular band indices had been reported. The red arm of the spectrograph was set so the spectra cover the range 5950 Å < λ < 7650 Å.

The echelle spectra were reduced using IRAF routines as described in Woolf & Wallerstein (2005). The DIS spectra were reduced using standard IRAF routines to subtract the bias, divide by flat-field spectra, reduce to one-dimensional spectra, apply HeNeAr lamp spectra wavelength calibration, and do standard-star flux calibrations.

## 3. ANALYSIS

M and K dwarf atmospheric parameters were estimated using photometric $V$, $K_s$, and $H$ measurements (Cutri et al. 2003; Calibrating M Dwarf metallicities 219
Mermilliod et al. (1997) and parallax distances as described in Woolf & Wallerstein (2005). The magnitudes and parallaxes of the M and K dwarfs observed for this paper are listed in Table 1. For several stars we use the Hipparcos parallax of their brighter binary companion. Fe and Ti abundances were calculated for the 32 cool dwarf stars in Table 1 are listed in Table 2. Atmospheric parameters and the Fe and Ti abundances derived for the 32 cool dwarf stars in Table 1 are listed in Table 2. Themetallicity [M/H] parameter listed is the effective metallicity after correcting for the effect of non-solar $\alpha$-element to Fe abundance ratios as described in Woolf & Wallerstein (2005). The quoted abundance uncertainties include the effects

4. RESULTS

4.1. Chemical Abundances

The atmospheric parameters and the Fe and Ti abundances derived for the 32 cool dwarf stars in Table 1 are listed in Table 2. The metallicity [M/H] parameter listed is the effective metallicity after correcting for the effect of non-solar $\alpha$-element to Fe abundance ratios as described in Woolf & Wallerstein (2005). The quoted abundance uncertainties include the effects.
**TABLE 3**

**Binary and Cluster Abundances**

| Primary     | \( T_\text{eff} \) (K) | \( \log g \) | \( \xi \) (km s\(^{-1}\)) | \( n \) Lines | \( Fe \) \( ^{\dagger} \) | \( n \) Lines | \( Ti \) \( ^{\dagger} \) | \( n \) Lines | \( Ti \) \( ^{\dagger} \) | \( n \) Lines | Secondary | \( T \) (K) | \( Fe \) \( ^{\dagger} \) | \( Ti \) \( ^{\dagger} \) |
|-------------|----------------|-------------|----------------|-------------|-------|-------|-------|-------|-------|-------|------|--------|-------|-------|
| HIP 9094    | 5140           | 3.86        | 1.39           | 73.79 ± 0.05 | 45     | 7.55 ± 0.11 | 16     | 4.86 ± 0.09 | 15     | 4.87 ± 0.13 | 3     | HD 11964B | 3930 | 7.43 ± 0.09 | 5.04 ± 0.11 |
| HIP 12777   | 6200           | 4.25        | 1.60           | 74.3 ± 0.06  | 29     | 7.51 ± 0.09 | 7      | 4.98 ± 0.10 | 4      | 4.86 ± 0.10 | 2     | GJ 107B | 3710 | 7.51 ± 0.08 | 5.08 ± 0.09 |
| HIP 13642   | 5150           | 4.52        | 0.50           | 78.0 ± 0.08  | 33     | 7.82 ± 0.10 | 17     | 5.54 ± 0.10 | 34     | 5.31 ± 0.13 | 2     | HD 18143B | 3970 | 7.64 ± 0.11 | 5.09 ± 0.13 |
| HIP 14286   | 5570           | 4.37        | 1.08           | 70.9 ± 0.07  | 29     | 7.10 ± 0.11 | 13     | 4.88 ± 0.09 | 16     | 4.80 ± 0.17 | 5     | LHS 1494 | 3410 | 7.46         | 5.15         |
| HIP 26779   | 5135           | 4.54        | 0.50           | 76.5 ± 0.06  | 26     | 7.81 ± 0.10 | 10     | 5.16 ± 0.09 | 16     | 5.41 ± 0.18 | 4     | HIP 26801 | 3725 | 7.61 ± 0.09 | 5.11 ± 0.10 |
| HIP 28671   | 5500           | 4.42        | 0.94           | 65.3 ± 0.08  | 34     | 6.38 ± 0.12 | 8      | 4.24 ± 0.12 | 5      | 4.11 ± 0.14 | 2     | BD +19 1185B | 3820 | 6.51 ± 0.07 | 4.02 ± 0.08 |
| HIP 32423   | 4830           | 4.71        | 0.75           | 72.7 ± 0.06  | 29     | 7.40 ± 0.17 | 6      | 4.86 ± 0.09 | 17     | 4.98 ± 0.11 | 3     | HD 263175B | 3650 | 7.20 ± 0.07 | 4.77 ± 0.08 |
| HIP 50384   | 6030           | 4.27        | 1.57           | 70.6 ± 0.05  | 24     | 7.08 ± 0.10 | 13     | 4.68 ± 0.09 | 6      | 4.68 ± 0.10 | 4     | BD +23 2207B | 3740 | 7.12 ± 0.06 | 4.74 ± 0.08 |
| HIP 67308   | 4085           | 4.57        | 1.4            | 7.29 ± 0.10  | 15     | ...     | ...   | 4.76 ± 0.11 | 34     | ...     | ...   | ...     | ...   | ...     | ...     |
| HIP 86036   | 5710           | 4.38        | 1.17           | 73.4 ± 0.05  | 27     | 7.63 ± 0.10 | 8      | 4.99 ± 0.07 | 13     | 5.06 ± 0.13 | 4     | HIP 86087 | 3750 | 7.46 ± 0.08 | 5.03 ± 0.10 |
| HIP 114156  | 4250           | 4.69        | 1.0            | 7.38 ± 0.08  | 24     | ...     | ...   | 4.93 ± 0.10 | 39     | ...     | ...   | G 275-2  | 3225 | 7.72         | 5.28         |
| Hyades \( ^{a} \) | ... | ...     | ...   | 7.58 ± 0.01 | ...     | ...   | ... | 5.18 ± 0.01 | ...     | ...     | ...   | BD +17 719C | 4185 | 7.49 ± 0.09 | 4.97 ± 0.11 |
| Hyades \( ^{a} \) | ... | ...     | ...   | 7.58 ± 0.01 | ...     | ...   | ... | 5.18 ± 0.01 | ...     | ...     | ...   | GJ 3290 | 3630 | 7.55 ± 0.11 | 5.04 ± 0.13 |
| Hyades \( ^{a} \) | ... | ...     | ...   | 7.58 ± 0.01 | ...     | ...   | ... | 5.18 ± 0.01 | ...     | ...     | ...   | GJ 3278 | 3745 | 7.59 ± 0.10 | 4.14 ± 0.11 |
| Hyades \( ^{a} \) | ... | ...     | ...   | 7.58 ± 0.01 | ...     | ...   | ... | 5.18 ± 0.01 | ...     | ...     | ...   | LP 13-691 | 3955 | 7.51 ± 0.11 | 4.96 ± 0.13 |
| Hyades \( ^{a} \) | ... | ...     | ...   | 7.58 ± 0.01 | ...     | ...   | ... | 5.18 ± 0.01 | ...     | ...     | ...   | HD 285804 | 4210 | 7.55 ± 0.09 | 5.09 ± 0.13 |
| HIP 75069   | 5185           | 4.64        | 0.50           | 7.21 ± 0.04  | 27     | 7.30 ± 0.09 | 10     | 4.79 ± 0.07 | 14     | 4.80 ± 0.14 | 4     | LTT 14560 | ... | ...     | ...     |
| HIP 97675   | 6010           | 4.05        | 1.84           | 7.46 ± 0.06  | 28     | 7.40 ± 0.11 | 12     | 4.93 ± 0.09 | 5      | 4.88 ± 0.12 | 5     | GJ 7681B | ... | ...     | ...     |
| HIP 99452   | 5250           | 4.55        | 0.58           | 7.48 ± 0.07  | 25     | 7.42 ± 0.07 | 8      | 5.32 ± 0.09 | 15     | 5.11 ± 0.17 | 4     | GJ 2832B | ... | ...     | ...     |

\( ^{a} \) Abundances in this table are reported as \( A(X) = \log (N_X/N_H) + 12.00 \).

\( ^{b} \) Hyades abundances from Paulson et al. (2003).
of uncertainty in temperature, gravity, and microturbulence and the scatter of abundances determined from different lines in the same star. The temperature and gravity uncertainties listed in Table 2 are the uncertainties derived from uncertainties in the input parallax and photometry data and do not include the effects of possible systematic errors, which could possibly be as large as about ±100 to 200 K for the temperature uncertainty, and ±0.3 to 0.4 for log g.

To test our method of calculating abundances in cool dwarf stars, we observed binaries with a cool dwarf secondary and a warmer dwarf primary. These were selected to have large enough angular separations that each component could be observed individually. Most primaries were F or G dwarfs. We also observed five cool dwarfs in the Hyades. The rationale for this test is that members of a binary or a cluster that formed from the same material should have the same chemical composition. Diffusion and nuclear enrichment processes, which can change photospheric abundances, should not have any measurable effect in these unevolved stars. The model atmospheres and methods used to find abundances in F and G dwarfs are well established. The good agreement between solar system meteoritic and solar photosphere abundances for most elements is evidence that the photospheric abundances calculated for solar-type stars using these models and methods are reasonable. If our method for calculating abundances in cool dwarfs is accurate, then the abundances should agree with those calculated for their warmer binary or cluster companions.

The binary abundances are compared in Table 3 and Figure 1. The reported F and G dwarf abundance uncertainties include the effects of uncertainty in temperature, gravity, microturbulence, and the scatter of abundances determined from different lines. Temperature uncertainties due to uncertainties in the Strömgren photometry of the warm stars are less than 40 K. The temperature uncertainty and the uncertainties in determining the mass and bolometric magnitude for the warm stars correspond to Δ log g < 0.10. We find that the binary and cluster Fe i abundances agree to within the combined uncertainties, except for those with cool dwarfs with $T_{\text{eff}} < 3500$ K, which are indicated by open circles in the figure. The same pattern is seen for the Ti i abundances, except that HD 18143B, BD +19 1185B, BD +17 791C, and LP 13-691 have a bit smaller abundance estimates than their warmer companions, even allowing for the uncertainties. Our method of measuring chemical abundances in cool dwarfs appears to provide accurate results for stars with temperatures greater than 3500 K. A weakness of this test is that we were able to observe only one such binary with [Fe/H] < −0.5: low-metallicity stars are less common, and identifying low-metallicity cool dwarfs that are also in widely separated visual binaries with F or G dwarf companions is even more difficult.

The fact that we calculate similar abundances for both members of the binaries where the cooler member is warmer than 3500 K implies that the abundances we find for the warmer stars are not significantly affected by the possible problems caused by molecular bands. The metallicities of the binaries we studied were close to the solar metallicity. Stars of lower metallicity would be less affected by weak line blanketing.

There appears to be a systematic error causing the calculated abundances for stars cooler than 3500 K to be too large. It may be that the model atmospheres used do not sufficiently model the H2O opacity, which starts to become much stronger at temperatures cooler than about 3500 K. It is also possible that increasing molecular band strengths at the cooler temperatures depress the apparent continuum in a molecular line haze, leading us to overestimate the atomic-line equivalent widths. We note that because of this result, we are no longer certain of the

![Fig. 1.—Cluster or binary warm star vs. cool star Fe abundance comparison. Open circles indicate the secondary stars with $T_{\text{eff}} < 3500$ K. The diagonal line indicates the location of perfect agreement.](image1)

![Fig. 2.—Temperature vs. CaH2 index for program stars. The line is a least-squares fit: $T_{\text{eff}} = (2696 + 1618 \times \text{CaH2})$ K.](image2)


4.2. Molecular Index–Metallicity Calibration

The molecular indices and Fe abundances used for the metallicity calibration are listed in Table 4. The stars listed include all those from this paper and Woolf & Wallerstein (2005) for which molecular index data are available, and 12 more from the other published reports. The abundances used for cool dwarfs in binaries with an F, G, or early K star are those of their warmer star. Abundances for stars in the Hyades or in a binary with two cool stars warmer than 3500 K are given by the average cluster or binary abundance. The uncertainties of the CaH2 and TiO5 index measurements are about ±0.04 (Reid et al. 1995), or ±5% to 10% (Zapatero Osorio & Martín 2004).

CaH2 is well correlated with effective temperature, as shown in Figure 2. TiO5 depends on temperature and metallicity. The last three binaries in Table 3 have secondaries that are too cool for measuring abundances. We will assume that they have the abundances of their warmer companions.

Table 4

| Star | Teff | [Fe/H] | CaH2 | TiO5 | Fe | Index |
|------|------|-------|------|------|----|-------|
| HIP 1386 | 3600 | 0.16 | 0.56 | 0.59 | 1 | 1 |
| HIP 17743 | 3685 | −0.30 | 0.62 | 0.73 | 1 | 7 |
| HIP 26801 | 3725 | 0.20 | 0.62 | 0.71 | 2 | 7 |
| HIP 27928 | 4370 | −0.73 | 0.97 | 0.96 | 3 | 1 |
| HIP 37798 | 4135 | 0.10 | 0.80 | 0.89 | 1 | 7 |
| HIP 59514 | 3845 | −0.05 | 0.69 | 0.79 | 1 | 7 |
| HIP 67308 | 4085 | −0.13 | 0.73 | 0.93 | 2 | 1 |
| HIP 86087 | 3750 | −0.11 | 0.64 | 0.71 | 2 | 7 |
| HIP 89490 | 3660 | −0.53 | 0.66 | 0.77 | 1 | 7 |
| HIP 98306 | 3670 | −0.62 | 0.56 | 0.77 | 1 | 6 |
| HIP 105932 | 3680 | −0.37 | 0.67 | 0.73 | 1 | 7 |
| HIP 117383 | 3560 | −0.33 | 0.53 | 0.66 | 1 | 1 |
| HD 7895B | 4000 | −0.07 | 0.76 | 0.85 | 1 | 7 |
| HD 11964B | 3930 | −0.06 | 0.74 | 0.79 | 2 | 7 |
| HD 18143B | 3970 | 0.35 | 0.78 | 0.86 | 2 | 7 |
| HD 18143C | ... | 0.35 | 0.41 | 0.40 | 2 | 7 |
| HD 33793 | 3570 | −0.99 | 0.59 | 0.81 | 3 | 6 |
| HD 36395 | 3760 | 0.21 | 0.58 | 0.65 | 3 | 7 |
| HD 88230 | 3970 | −0.03 | 0.79 | 0.88 | 3 | 7 |
| HD 95755 | 3510 | −0.42 | 0.53 | 0.60 | 3 | 7 |
| HD 97101B | 3610 | 0.02 | 0.57 | 0.62 | 3 | 7 |
| HD 119850 | 3650 | −0.10 | 0.60 | 0.64 | 3 | 7 |
| HD 178126 | 4530 | −0.72 | 0.93 | 0.97 | 3 | 1 |
| HD 199305 | 3720 | −0.13 | 0.63 | 0.71 | 3 | 7 |
| HD 217987 | 3680 | −0.22 | 0.61 | 0.69 | 3 | 1 |
| HD 263175B | 3655 | −0.18 | 0.60 | 0.72 | 2 | 7 |
| HD 285804 | 4210 | 0.13 | 0.81 | 0.86 | 2 | 1 |
| BD −1 293B | 4310 | −0.09 | 0.87 | 0.94 | 1 | 1 |
| GL 81.1B | ... | 0.09 | 0.74 | 0.79 | 4 | 7 |
| GL 105B | ... | −0.19 | 0.41 | 0.38 | 4 | 7 |
| GL 107B | 3715 | −0.02 | 0.57 | 0.63 | 2 | 7 |
| GL 129 | 3965 | −1.66 | 0.86 | 1.01 | 1 | 6 |
| GL 166C | ... | −0.33 | 0.36 | 0.34 | 4 | 7 |
| GL 212 | ... | 0.04 | 0.62 | 0.71 | 4 | 7 |
| GL 231.1B | ... | −0.02 | 0.41 | 0.44 | 4 | 7 |
| GL 250B | ... | −0.15 | 0.50 | 0.59 | 4 | 7 |
| GL 283.2B | ... | 0.03 | 0.40 | 0.39 | 2 | 7 |
| GL 297.2B | ... | −0.09 | 0.49 | 0.56 | 4 | 7 |

Source:

1) This paper; 2) this paper: binary or cluster abundance; 3) Woolf & Wallerstein 2005; 4) Bonfils et al. 2005; 5) Fulbright 2000; 6) Gizis 1997; 7) Reid et al. 1995 and Hawley et al. 1996.

Abundances reported for LHS 450 in Woolf & Wallerstein (2005), the only $T_{\text{eff}} < 3500$ K star in that paper.

It should be possible, however, to calibrate our molecular index versus metallicity correlation to lower temperatures by including visual binaries. The last three binaries in Table 3 have secondaries that are too cool for measuring abundances. We will assume that they have the abundances of their warmer companions.
We were unable to find an empirical polynomial fit to the data that corresponds well to the data. We have estimated the locations of equal-metallicity lines in CaH2 versus TiO5 by eye, as shown in Table 5 and Figure 4. Because the molecular band strengths decrease at higher temperatures, the fits start to converge for CaH2 \( \gtrsim 0.8 \), or \( T_{\text{eff}} \gtrsim 4000 \) K. Molecular band strengths are poor indicators of metallicity at temperatures where the bands are very weak and the molecular index uncertainties correspond to large metallicity uncertainty. The \( \pm 0.04 \) molecular index uncertainties correspond to an \([Fe/H]\) uncertainty of about \( \pm 0.3 \) through the entire region covered by our calibration grid.

5. DISCUSSION

We have now determined the Fe and Ti abundances for 84 M and K dwarf stars using high-resolution spectra and equivalent width abundance analysis. We have tested our analysis method using stars in binaries and a cluster and find that it appears to give reliable abundances for stars warmer than 3500 K.

When we include abundance data for 12 stars from other researchers, we have 76 stars with measured Fe abundances and CaH2 and TiO5 indices. We have used these to create a rough molecular index–metallicity calibration.

The main shortcoming of our data is that we have few low-metallicity stars with \( T_{\text{eff}} < 4000 \) K. Our data are not yet sufficient to determine whether the difficulty in identifying very low metallicity stars is partly caused by an “M dwarf problem” similar to the G dwarf problem, where low-metallicity stars are less common than predicted by Galactic star formation and chemical evolution models. At a given temperature, low-metallicity stars are fainter than solar metallicity stars; they are “subdwarfs.” This means they must be physically closer to appear bright enough to obtain a spectrum with sufficient signal.

We have been granted time on the Hobby-Eberly Telescope to observe several M dwarf stars with CaH2 and TiO5 indices that indicate they have \([Fe/H]\) \( < -1.0 \), but that are too faint to observe with APO. The abundances calculated from these spectra will help populate the low-metallicity region of the CaH2-TiO5 plane.

When the calibration is adequately defined, it will be possible to estimate the metallicities of thousands of cool dwarf stars. Thousands of spectra of red dwarf stars have already been observed in the Sloan Digital Sky Survey. While the abundances estimated through a molecular index calibration will necessarily have larger uncertainties than those calculated through the analysis of atomic line strengths in high-resolution spectra, they will be sufficient to allow statistical studies of the relative numbers of cool dwarfs of different metallicities, and a determination whether the G dwarf problem continues to
TABLE 5
CaH2, TiO5, [Fe/H] Grid Points

| [Fe/H] | CaH2 | TiO5 | CaH2 | TiO5 | CaH2 | TiO5 | CaH2 | TiO5 |
|--------|------|------|------|------|------|------|------|------|
| 0.05   | 0.35 | 0.30 | 0.35 | 0.39 | ...  | ...  | ...  | ...  |
| 0.50   | 0.40 | 0.37 | 0.40 | 0.47 | ...  | ...  | ...  | ...  |
| 0.55   | 0.50 | 0.45 | 0.50 | 0.55 | 0.45 | 0.65 | 0.45 | 0.65 |
| 0.60   | 0.55 | 0.55 | 0.55 | 0.71 | 0.55 | 0.83 | 0.55 | 0.83 |
| 0.65   | 0.60 | 0.60 | 0.60 | 0.77 | 0.60 | 0.87 | 0.60 | 0.87 |
| 0.70   | 0.65 | 0.65 | 0.65 | 0.80 | 0.65 | 0.91 | 0.65 | 0.91 |
| 0.80   | 0.70 | 0.70 | 0.70 | 0.83 | 0.70 | 0.91 | 0.70 | 0.91 |
| 0.85   | 0.76 | 0.76 | 0.76 | 0.89 | 0.76 | 0.98 | 0.76 | 0.98 |
| 0.90   | 0.86 | 0.86 | 0.86 | 0.93 | 0.86 | 0.98 | 0.86 | 0.98 |

Fig. 4.—Equal-metallicity contours in CaH2 vs. TiO5.

lower masses; i.e., whether low-metallicity M dwarfs are more scarce than models predict.

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