71-15,101

BOLTON, Charles Thomas, 1943-
LOW-DISPERSION LUMINOSITY CRITERIA IN A AND F TYPE STARS.

The University of Michigan, Ph.D., 1970
Astronomy

University Microfilms, A XEROX Company, Ann Arbor, Michigan

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED

# LOW-DISPERSION LUMINOSITY CRITERIA IN A AND F TYPE STARS

by

Charles Thomas Bolton

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Astronomy)
in The University of Michigan
1970

Doctoral Committee:

Associate Professor Charles R. Cowley, Chairman
Assistant Professor Jack G. Hills
Associate Professor Gordon L. Kane
Associate Professor Richard L. Sears

ABSTRACT

LOW-DISPERSION LUMINOSITY CRITERIA IN A AND F TYPE STARS

by

Charles Thomas Bolton

Chairman: Charles R. Cowley

Using the technique of spectral synthesis we have investigated some of the luminosity criteria used in the low-dispersion spectral classification of A and F stars. We find that for stars with solar abundances the ratio λ4178:λ4481 is at least as sensitive to microturbulence as it is to surface gravity. This implies that the microturbulent velocity is inversely correlated with surface gravity with very little scatter for A and F stars.

We find that, qualitatively, Am spectra are duplicated best by a model with log g = 4.3, abnormal abundances like those found by V'ant Veer-Menneret (1963) or Conti (1965) and the same microturbulence as stars with solar abundances. The "anomalous luminosity effect" in Am stars between the ratios λ4178:λ4172 and λ4417:λ4481 is attributed to the abundance of titanium. Some of the consequences for spectral classification from the possible variation of microturbulence and abundances at a given spectral type and luminosity class are discussed.

This investigation demonstrates that, even with our present limited knowledge of the values and ranges of such parameters as microturbulence and abundances as a function of spectral type and luminosity class, spectral classification is a very powerful tool for studying stellar atmospheres.

## PREFACE

This thesis would never have been written without the immense assistance of Dr. Charles R. Cowley. He rescued me when advisers were deserting me left and right and proposed this thesis topic. He then kept my feet on the ground when I was ready to chuck my career as a graduate student. Finally, he very patiently guided me as I learned my way around a subject that was almost completely new to me. I will be forever in his debt.

Part of this work was done while I was supported by a NASA Traineeship, and the great portion of it was funded by the National Science Foundation through a grant to Dr. Cowley. I am grateful to both of these organizations.

My wife, Mary, has contributed immeasurably to this work by her constant love and encouragement and by her willingness to work full-time at jobs that were often menial and unpleasant. In addition both her family and mine have contributed to our moral and financial support during this time. Their support has enabled me to complete this work without having to earn an honest living.

Many graduate students have contributed to this work. Chief among these were Wayne Fullerton and Richard Bochonko who helped with the programming; Carol Everett, who

devised one of the integration routines and gave general advice; and Jim LoPresto.

Dr. Guenther Elste and Dr. Margo Aller gave advice and Dr. Elste loaned me his atmosphere program. Dr. Anne Cowley was kind enough to loan me some of her spectral classification plates. The aid of these staff members was invaluable in the completion of this project. I would also like to thank Myron Smith for sending me some of his results in advance of publication.

Finally I would like to thank people such as Drs. K. M. Yoss, Stanley P. Wyatt, Helmut Abt, William P. Bidelman, and Barry M. Lasker whose help, encouragement and inspiration have played an important role in my short career as an astronomer.

TABLE OF CONTENTS


| | Page |
|---|---|
| PREFACE | ii |
| LIST OF TABLES | v |
| LIST OF FIGURES | vi |
| I. INTRODUCTION | 1 |
| II. SPECTRAL CLASSIFICATION OF A AND F STARS | 2 |
| III. CALCULATIONS | 5 |
| A. Model Atmospheres | 5 |
| B. Line Profile Calculations | 7 |
| C. The System of Oscillator Strengths | 11 |
| D. Instrumental Profile | 18 |
| IV. RESULTS | 22 |
| V. DISCUSSION | 33 |
| REFERENCES | 39 |

LIST OF TABLES


| Table | | Page |
|---|---|---|
| 1. | Abundances assumed for model atmosphere and line profile calculations. | 6 |
| 2. | Coefficients for the polynomial approximation of partition functions for ions that have not previously been published. | 9 |
| 3. | Zero-point coefficients for the rare earths. | 10 |
| 4. | Lines computed in synthesizing the region around λλ4172-78. | 12 |
| 5. | Lines computed in synthesizing the region around λ4417. | 14 |
| 6. | Lines computed in synthesizing the region around λ4481. | 16 |
| 7. | Sources of gf values. | 17 |

LIST OF FIGURES


| Figure | | Page |
|---|---|---|
| 1. | Example of synthetic and convolved synthetic spectra for λλ4172-78 region. | 19 |
| 2. | Example of synthetic and convolved synthetic spectra for λ4417 region. | 20 |
| 3. | Example of synthetic and convolved synthetic spectra for λ4481 region. | 21 |
| 4. | Convolved synthetic spectra computed for solar abundances and varying surface gravity. | 23 |
| 5. | Convolved synthetic spectra showing the effect of varying surface gravity and microturbulence. | 24 |
| 6. | Convolved synthetic spectra showing the effect of varying the microturbulence at constant surface gravity for stars with solar abundances. | 27 |
| 7. | The convolved synthetic spectrum for an Am star compared with those for a dwarf and a giant star with solar abundances. | 30 |
| 8. | The convolved synthetic spectrum for an Am star with high microturbulence compared with a giant star with solar abundances. | 34 |

# I. INTRODUCTION

A low-dispersion spectrogram of a star contains a wealth of information about that star's physical characteristics. This information in the form of spectral types and luminosity classes has been tremendously important in helping unravel such problems as stellar evolution and galactic structure.

Low-dispersion spectra are also very powerful discriminators of the physical properties of stellar atmospheres. The appearance of the spectral features used in classification depends upon the physical properties of the stellar atmosphere where the spectrum is formed. Clearly there is a very close correlation between the properties of stellar atmospheres and the spectral classes. If the behavior of the various spectral features could be calibrated quantitatively in terms of the physical parameters of stellar atmospheres (effective temperature, surface gravity, microturbulence, abundance), then a very powerful tool for the study of stellar atmospheres would be available. This is an aspect of low-dispersion spectroscopy that has been almost totally ignored. This paper describes a preliminary investigation of the feasibility of obtaining such a calibration. We will show that with only a qualitative calibration it is possible to obtain very useful information concerning the atmospheres of A and F stars.

## II. SPECTRAL CLASSIFICATION OF A AND F STARS

Spectral classification is difficult for the A and early F type stars. Over the early part of this range there are very few features visible in the photographic spectra. Those that are available for classification purposes are either very strong or very weak. The situation is further complicated by the large proportion of peculiar stars (the Ap and Am stars) that is found throughout this spectral range. The physical properties of these stars are not completely understood, and this has made spectral classification more difficult. For example, various investigators have not been able to agree on the definition of Am stars (cf. Barry 1970).

Most, though not all, of the classification problems in this spectral range involve difficulties with luminosity or abundance criteria. This investigation is an attempt to calibrate the luminosity criteria for A and F stars in terms of their physical parameters. We are interested in determining the behavior of the low-dispersion luminosity criteria as a function of surface gravity, microturbulent velocity, and abundance.

Spectral classification of A and F type stars depends largely upon the appearance of blended features in their spectra. Only in the case of the very strongest features, such as

the hydrogen lines or the Ca II K-line, is it possible to unequivocally explain the behavior of a feature in terms of the behavior of a single ion. This is true of the luminosity criteria used by Cowley, Cowley, Jaschek, and Jaschek (1969), hereafter called $C^2J^2$, in their classification of the bright A stars. Two line ratios that were used are λ4178:λ4172 and λ4417:λ4481. Both of these ratios increase with increasing luminosity. All four spectral features are heavily blended although λ4481 is dominated by a Mg II doublet. This feature appears to change very little with luminosity on low dispersion plates.

Visual inspection of the regions at λ4417 and λλ4172-78 on coudé plates or tracings from coudé plates (Wright 1964; Hiltner and Williams 1946) of stars of different luminosities reveals no obvious changes in the appearance of lines in these regions. Therefore the changes seen on low dispersion plates must be due to the collective behavior of the lines in the blend. We would like to determine

1) What physical changes in the stellar atmospheres change the spectral appearance? That is, are changes caused by changes in surface gravity, some other parameter, or a combination?
2) What is the nature of the change in appearance of the blend? Does the line depth change, the width, or both?

3) Do the classification criteria depend critically on the technique used to obtain the spectra?

Another intriguing problem arising in the classification of A and F stars is the "anomalous luminosity effect" found in Am stars. By this phrase we mean that different luminosity criteria give different results. Specifically, according to $C^2J^2$, the appearance of the $\lambda\lambda$4172-78 region of Am stars is characteristic of luminosity class III. The ratio of $\lambda$4417:$\lambda$4481, on the other hand, is small and more typical of stars of luminosity class V. Clearly some physical parameter other than surface gravity must be invoked to explain this effect. We would like to know whether the discrepancy can be explained in terms of normal stellar atmospheres with peculiar abundances (e.g. V'ant Veer-Menneret 1963; Conti 1965) or whether it is necessary to invoke some other explanation.

## III. CALCULATIONS

We have investigated the above questions by synthesizing the spectral features at λ4417, λ4481, and λλ4172-78 for a variety of different physical conditions (temperature, surface gravity, microturbulence, and abundance). These synthetic spectra were then convolved with an instrumental profile corresponding to that for low-dispersion spectra and the results intercompared. They were also compared with results from the visual inspection of plates of classification dispersion and with plates in the Yerkes Atlas (Morgan, Keenan, and Kellman 1943).

### A. Model Atmospheres

Scaled model atmospheres in hydrostatic equilibrium were constructed using a program kindly made available by G. Elste (cf. Elste 1964). Sources of continuous opacity included (1) bound-free and free-free absorption by neutral hydrogen and neutral helium, the most abundant metals, and the $H^-$ and $H_2^+$ ions, (2) electron scattering, and (3) Rayleigh scattering. The computed opacities were compared with those of Bode (1965) and found to be in excellent agreement. Series of models were computed for two different temperatures, 8200°K and 6800°K. The temperature distribution for most of the models was scaled from the Mihalas Balmer-line blanketed model (Mihalas 1966) characterized by $\theta_{eff} = 0.70$, log g = 4.0.

The temperature distribution for the log g = 2.5 models was scaled from the Mihalas Balmer-line blanketed model for $\theta_{eff}$ = 0.70, log g = 2.0.

At each temperature models were constructed for log g = 4.3, 3.4, and 2.5 assuming solar abundances (see Table 1). Another set of models was also constructed at each temperature for log g = 4.3 and 3.4 assuming metallic abundances (Table 1).

Table 1.

Abundances assumed for model atmosphere and line profile calculations (log $N_H$ = 0.00).

| Element | Solar[1] | Metallic[2] | Element | Solar[1] | Metallic[2] |
|---|---|---|---|---|---|
| C | -3.60 | -3.60* | Mn | -7.15 | -7.01 |
| Na | -5.70 | -5.70* | Fe | -5.45 | -4.88 |
| Mg | -4.64 | -5.66 | Ni | -6.22 | -5.32 |
| Si | -4.40 | -3.70 | Y | -9.80 | -8.69 |
| K | -7.05 | -7.05* | Zr | -9.35 | -8.77 |
| Ca | -5.62 | -6.71 | Ce | -10.22 | -8.88 |
| Sc | -9.15 | -9.85 | Pr | -10.55 | -9.16 |
| Ti | -7.37 | -7.12 | Sm | -10.38 | -9.04 |
| V | -7.85 | -7.58 | Eu | -11.04 | -9.65 |
| Cr | -6.88 | -6.18 | Gd | -10.87 | -9.48 |

* Adopted abundance
1 Muller, E. A. 1968.
2. V'ant Veer-Menneret, C. 1963.

V'ant Veer-Menneret's abundances for 63 Tauri were chosen because they represented extreme over-abundances for an Am star.

## B. Line Profile Calculations

The line profiles were calculated according to the methods described by Cowley (1970, sec. 2-12). LTE was assumed throughout. The line absorption coefficients include van der Waals broadening and quadratic Stark broadening. The quadratic Stark broadening was calculated for all lines by the formula given by Griem (1968). This approach was adopted in order to simplify the calculations for the large number of lines involved. Some calculations were tried with the Stark broadening decreased by a factor of five. In the worst case this had the effect of decreasing some line depths in the convoluted spectrum by 0.7 per cent.

The Stark broadening is not negligible for the Mg II doublet at $\lambda$4481. For these lines Griem's formula was adjusted to fit the broadening given by Griem (1964). An additional twenty-five per cent was then added to account for the quadrupole interactions (Hobbs and Cowley 1968). According to Hobbs and Cowley, our estimate of the quadratic Stark broadening is too small by twenty to twenty-five per cent. This is within the errors of the measured damping and has no significant effect on our results.

Van der Waals broadening was calculated according to the method given by Cowley (1970, sec. 6-11). The van der Waals broadening equation contains a free parameter, $\eta_o$, which

can be used to fit the calculations to line broadening data when it is available. For the iron lines $\eta_o$ was taken to be an average of the values calculated by Cowley, Elste, and Allen (1969) for some selected Fe I lines. Their enhancement factor, E, is related to $\eta_o$ by

$$\log \eta_o = -5/2 \log E. \qquad (1)$$

The adopted $\eta_o$'s for iron were 0.035. For most of the other lines no detailed line broadening data were available. For these $\eta_o = 0.2$ was adopted as a compromise between the theoretical value of 2/3 (cf. Unsöld 1955) and the sometimes considerably lower experimental results (cf. Cowley 1970).

Line profiles calculated by our program were checked against those calculated with a program written by Evans (1966) and found to be in excellent agreement.

Partition functions for the first, second, and third ions of each element were calculated using the polynomial approximation method described by Bolton (1970). Since atomic energy level tables were not available for the rare earths, we assumed that the shape of their partition functions is the same as for iron, and the zero-point coefficient, $a_o$, was then determined by fitting these polynomials to the partition functions given by Corliss and Bozman (1962) for T = 5100°K. Table 2 gives the polynomial coefficients for ions that have not been previously published. Table 3 gives the zero-point coefficients for the rare earths.

Table 2

Coefficients for the polynomial approximation of partition functions for ions that have not been previously published (cf. Bolton 1970).

| Ion | $g_o$ | $a_o$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ |
|---|---|---|---|---|---|---|
| Ca III | 1.0 | -100.000000 | | | | |
| Cr III | 1.0 | 3.086235 | -0.230190 | 0.309739 | 0.001543 | |
| Fe III | 9.0 | 2.582925 | -0.291880 | 0.361330 | -0.036512 | |
| Mg III | 1.0 | -100.000000 | | | | |
| Mn III | 6.0 | -3.784366 | -7.644204 | -3.125854 | -0.582502 | |
| Ni III | 9.0 | 2.008354 | -0.527168 | -0.182151 | -0.107461 | |
| Sc III | 10.0* | -100.000000 | | | | |
| Si I | 1.0 | 2.137494 | -0.230234 | -0.003700 | 0.065962 | 0.223756 |
| Si II | 2.0 | 1.308765 | -0.075758 | -0.127747 | -0.146298 | |
| Si III | 1.0 | -100.000000 | | | | |
| Ti III | 5.0 | 2.754654 | -0.298903 | 0.080547 | | |
| V III | 4.0 | 3.131064 | -0.357918 | 0.259504 | 0.077344 | |
| Y I | 4.0 | 2.057138 | -1.467491 | 0.968925 | 0.461505 | |
| Y II | 1.0 | 2.701945 | -0.780790 | 0.036736 | -0.011359 | |
| Y III | 4.0 | 1.634144 | -0.295411 | -0.084137 | -0.033708 | |
| Zr III | 5.0 | 2.632023 | -0.629433 | | | |

* Assumed $g_o$ to simplify calculation

Table 3

Zero-point coefficients for the rare earths.

| Ion | $g_o$ | $a_o$ | Ion | $g_o$ | $a_o$ |
|---|---|---|---|---|---|
| Ce I | 7.0* | 4.746371 | Eu III | 8.0* | -0.029192 |
| Ce II | 8.0 | 5.534490 | Pr I | 8.0* | 3.849312 |
| Ce III | 7.0* | 4.204915 | Pr II | 9.0 | 4.674288 |
| Gd I | 5.0 | 3.918305 | Pr III | 8.0* | 3.228905 |
| Gd II | 6.0 | 4.607149 | Sm I | 3.0* | 3.577378 |
| Gd III | 5.0* | 3.236178 | Sm II | 2.0 | 4.337816 |
| Eu I | 8.0 | 0.293964 | Sm III | 3.0* | 2.966540 |
| Eu II | 9.0 | 2.232591 | | | |

* Estimated

Line identifications for the synthesized regions were taken from the list for β Corona Borealis by Hiltner (1945). Some additional lines were added. These were primarily the weaker lines in multiplets whose stronger lines had already been identified. Those lines for which no oscillator strengths were available were not used. These were usually of negligible strength (Hiltner's intensities 0, 1, or 2). The few stronger lines that were not included were all at the edges of the synthesized regions where they could safely be ignored.

C. The System of Oscillator Strengths

Tables 4-7 give lists of the lines used in synthesizing each spectral region, their identification, gf value, and source of the gf value. All other line data were taken from Moore (1949). Oscillator strengths for the neutral iron lines were taken from Corliss and Tech (1968), and those for the first ions of the iron group elements were taken from Warner (1967). Most other gf values were taken from Corliss and Bozman (1962). Where appropriate these oscillator strengths were modified to agree with the results of Allen and Corliss (1963).

At present there is considerable controversy over the system of oscillator strengths (cf. Bridges and Wiese 1970; Takens 1970). This uncertainty in the oscillator strengths

Table 4

Lines computed in synthesizing the region around λλ4172-78

| λ | I.D. | Multiplet | gf | Source |
|---|---|---|---|---|
| 4162.732 | Gd II | 17 | 0.1780 | 1 |
| 63.092 | Gd II | 44 | 0.1319 | 1 |
| 63.625 | Cr I | 35 | 1.2010 | 1,2 |
| 63.644 | Ti II | 105 | 1.5850 | 4 |
| 64.015 | V II | 37 | 0.0170 | 4 |
| 64.134 | Ti I | 163 | 0.3239 | 1,2 |
| 64.800 | Fe I | 418 | 0.0208 | 3 |
| 65.519 | Cr I | 305 | 6.7600 | 1,2 |
| 65.606 | Ce II | 10 | 1.9080 | 1 |
| 66.311 | Ti I | 163 | 0.3895 | 1,2 |
| 67.804 | Ce II | 29 | 0.6160 | 1 |
| 67.862 | Fe I | 599 | 0.1680 | 3 |
| 67.960 | Fe I | | 0.1770 | 3 |
| 68.625 | Fe I | 689 | 0.0855 | 3 |
| 68.660 | Fe II | 22 | 0.0001 | 5 |
| 68.942 | Fe I | 694 | 0.1880 | 3 |
| 69.773 | Ce II | 161 | 0.6310 | 1 |
| 69.777 | Fe I | 693 | 0.0920 | 3 |
| 69.838 | Cr I | 278 | 3.2390 | 1,2 |
| 70.108 | Gd II | 35 | 0.0364 | 1 |
| 70.202 | Cr I | 278 | 2.7590 | 1,2 |
| 70.860 | Cr II | 181 | 0.0046 | 4 |
| 70.906 | Fe I | 482 | 0.5540 | 3 |
| 71.390 | Ce II | | 0.0563 | 1 |
| 4171.696 | Fe I | 941 | 0.8050 | 3 |
| 71.897 | Ti II | 105 | 1.3500 | 4 |
| 71.904 | Fe I | 650 | 0.2840 | 3 |
| 71.920 | Cr II | 18 | 0.0016 | 4 |
| 72.126 | Fe I | 649 | 1.3300 | 3 |
| 72.641 | Fe I | 689 | 0.4320 | 3 |
| 72.749 | Fe I | 19 | 0.0047 | 3 |
| 72.770 | Cr I | | 4.2650 | 1,2 |
| 73.450 | Fe II | 27 | 0.0098 | 4 |
| 73.537 | Ti II | 21 | 0.0199 | 4 |
| 73.556 | Gd II | 117 | 0.4795 | 1 |
| 73.926 | Fe I | 19 | 0.0021 | 3 |
| 74.088 | Ti II | 105 | 0.1448 | 4 |
| 74.917 | Fe I | 19 | 0.0046 | 3 |
| 75.640 | Fe I | 354 | 1.2400 | 3 |
| 75.890 | Fe I | 694 | 0.0200 | 5 |
| 75.945 | Cr I | 106 | 0.6455 | 1,2 |
| 76.080 | Ce II | 135 | 0.0725 | 1 |
| 76.571 | Fe I | 695 | 1.5100 | 3 |
| 76.600 | Mn I | | 4.6800 | 1,2 |
| 77.540 | Y II | 14 | 5.7500 | 1 |
| 77.597 | Fe I | 18 | 0.0038 | 3 |
| 78.019 | Sm II | 16 | 0.0795 | 1 |
| 78.390 | V II | 25 | 0.0219 | 4 |

Table 4 -- Continued

| λ | I.D. | Multiplet | gf | Source | λ | I.D. | Multiplet | gf | Source |
|---|---|---|---|---|---|---|---|---|---|
| 4178.855 | Fe II | 28 | 0.0100 | 4 | 4184.895 | Cr I | 155 | 0.9350 | 1,2 |
| 79.257 | Cr I | 179 | 4.5650 | 1,2 | 84.895 | Fe I | 355 | 0.8750 | 3 |
| 79.430 | Cr II | 26 | 0.0814 | 4 | 85.334 | Ce II | 124 | 0.1621 | 1 |
| 79.810 | Zr II | 99 | 0.3318 | 1 | 86.119 | Ti I | 129 | 1.3810 | 1,2 |
| 81.500 | Cr II | 181 | 0.0024 | 4 | 86.359 | Cr I | 249 | 1.9500 | 1,2 |
| 81.550 | Fe I | 763 | 0.2830 | 3 | 86.599 | Ce II | 1 | 4.6800 | 1 |
| 81.758 | Fe I | 354 | 2.8300 | 3 | 87.044 | Fe I | 152 | 1.4800 | 3 |
| 82.384 | Fe I | 476a | 0.4490 | 3 | 87.323 | Ce II | 86 | 0.3470 | 1 |
| 82.790 | Fe I | 694 | 0.2340 | 3 | 87.590 | Fe I | 694 | 0.6070 | 3 |
| 83.025 | Fe I | 697 | 0.0707 | 3 | 87.802 | Fe I | 152 | 1.3500 | 3 |
| 83.435 | V II | 37 | 0.1700 | 4 | 88.099 | Gd II | 17 | 0.0234 | 1 |
| 84.252 | Gd II | 15 | 0.7600 | 1 | 88.128 | Sm II | 50 | 0.1820 | 1 |
| 84.329 | Ti II | 21 | 0.0276 | 4 | | | | | |

Table 5

Lines computed in synthesizing the region around λ4417.

| λ | I.D. | Multiplet | gf | Source | λ | I.D. | Multiplet | gf | Source |
|---|---|---|---|---|---|---|---|---|---|
| 4395.848 | Ti II | 61 | 0.0295 | 4 | 4409.519 | Ti II | 61 | 0.0085 | 4 |
| 96.580 | Ce II | | 0.0795 | 1 | 10.304 | Cr I | 129 | 0.4790 | 1,2 |
| 98.020 | Y II | 5 | 0.0563 | 1 | 10.641 | Ce II | 33 | 1.1490 | 1 |
| 98.314 | Ti II | 61 | 0.0081 | 4 | 11.093 | Cr I | 129 | 1.2100 | 1,2 |
| 98.787 | Ce II | 81 | 0.1071 | 1 | 11.080 | Ti II | 115 | 0.8500 | 4 |
| 99.203 | Ce II | 81 | 0.1660 | 1 | 11.878 | Mn I | | 2.3430 | 1,2 |
| 99.767 | Ti II | 51 | 0.0794 | 4 | 11.936 | Ti II | 61 | 0.0078 | 4 |
| 4400.355 | Sc II | 14 | 0.1349 | 1,2 | 12.250 | Cr I | 22 | 0.0078 | 1,2 |
| 00.575 | V I | 22 | 0.2819 | 1,2 | 13.040 | Zr I | 61 | 0.4570 | 1 |
| 01.293 | Fe I | 828 | 0.8640 | 3 | 13.600 | Fe II | 32 | 0.0010 | 4 |
| 01.547 | Ni I | 86 | 6.0300 | 1,2 | 13.866 | Cr I | 234 | 2.2920 | 1,2 |
| 03.350 | Zr II | 79 | 0.0776 | 1 | 14.540 | Zr II | 79 | 0.0870 | 1 |
| 03.360 | Sm II | 22 | 0.0276 | 1 | 14.879 | Mn I | 22 | 1.9500 | 1,2 |
| 04.276 | Ti I | 218 | 4.1650 | 1,2 | 15.125 | Fe I | 41 | 0.2883 | 6 |
| 04.752 | Fe I | 41 | 0.7590 | 6 | 15.559 | Sc II | 14 | 0.1023 | 1,2 |
| 05.849 | Pr II | 4 | 0.1289 | 1 | 16.474 | V I | 22 | 0.1259 | 1,2 |
| 06.641 | V I | 22 | 0.5010 | 1,2 | 16.817 | Fe II | 27 | 0.0081 | 4 |
| 06.670 | Gd II | 103 | 0.5755 | 1 | 17.274 | Ti I | 161 | 1.6220 | 1,2 |
| 07.278 | Ce II | 64 | 0.1289 | 1 | 17.718 | Ti II | 40 | 0.0661 | 4 |
| 07.678 | Ti II | 51 | 0.0087 | 4 | 18.340 | Ti II | 51 | 0.0214 | 4 |
| 07.714 | Fe I | 68 | 0.0676 | 3 | 18.784 | Ce II | 2 | 1.0720 | 1 |
| 08.419 | Fe I | 68 | 0.1120 | 3 | 19.032 | Gd II | 15 | 0.0912 | 1 |
| 08.248 | Gd II | 44 | 0.0794 | 1 | 20.450 | Zr I | 61 | 0.5495 | 1 |
| 08.844 | Pr II | 4 | 0.1446 | 1 | 20.526 | Sm II | 32 | 0.1350 | 1 |
| 09.220 | Ti II | 61 | 0.0085 | 4 | 21.138 | Sm II | 37 | 0.0977 | 1 |

Table 5 -- Continued

| λ | I.D. | Multiplet | gf | Source | λ | I.D. | Multiplet | gf | Source |
|---|---|---|---|---|---|---|---|---|---|
| 4421.240 | Gd II | 103 | 0.2399 | 1 | 4424.281 | Cr I | 129 | 1.1750 | 1,2 |
| 21.949 | Ti II | 93 | 0.0725 | 4 | 24.339 | Sm II | 45 | 0.3801 | 1 |
| 22.570 | Fe I | 350 | 0.6030 | 3 | 25.441 | Ca I | 4 | 0.4700 | 1 |
| 22.823 | Ti I | 78 | 0.1412 | 1,2 | 26.151 | Gd II | 14 | 0.0110 | 1 |
| 23.678 | Ce II | 21 | 0.3315 | 1 | 27.098 | Ti I | 128 | 2.8190 | 1,2 |
| 24.102 | Gd II | 67 | 0.0537 | 1 | 27.312 | Fe I | 2 | 0.0031 | 3 |

Table 6

Lines computed in synthesizing the region around λ4481

| λ | I.D. | Multiplet | gf | Source | λ | I.D. | Multiplet | gf | Source |
|---|---|---|---|---|---|---|---|---|---|
| 4470.483 | Ni I | 86 | 4.1650 | 1,2 | 4482.257 | Fe I | 68 | 0.2950 | 3 |
| 70.864 | Ti II | 40 | 0.1586 | 4 | 82.688 | Ti I | 113 | 0.2630 | 1,2 |
| 71.238 | Ti I | 146 | 1.2300 | 1,2 | 82.750 | Fe I | 828 | 0.4860 | 3 |
| 71.240 | Ce II | 8 | 1.0000 | 1 | 83.328 | Gd II | 62 | 0.2000 | 1 |
| 71.290 | Gd II | 82 | 0.1700 | 1 | 83.900 | Ce II | 3 | 0.7300 | 1 |
| 72.792 | Mn I | 22 | 0.8510 | 1,2 | 84.227 | Fe I | 828 | 1.7100 | 3 |
| 72.921 | Fe II | 37 | 0.0002 | 8 | 85.150 | Eu II | 26 | 0.4600 | 1 |
| 74.714 | V I | 101 | 1.5850 | 1,2 | 85.679 | Fe I | 830 | 0.6180 | 3 |
| 74.852 | Ti I | 113 | 0.2515 | 1,2 | 86.352 | Gd II | 135 | 1.0230 | 1 |
| 75.345 | Cr I | 95 | 0.7940 | 1,9 | 86.909 | Ce II | 57 | 0.2400 | 1 |
| 76.062 | Fe I | 830 | 3.0500 | 3 | 88.319 | Ti II | 115 | 1.0000 | 4 |
| 78.640 | Mn II | | 0.1202 | 4 | 88.917 | Fe I | 213 | 0.0112 | 3 |
| 78.795 | Gd II | 15 | 0.0700 | 1 | 89.089 | Ti I | 146 | 1.3500 | 1,2 |
| 79.359 | Ce II | 203 | 0.3700 | 1 | 89.185 | Fe II | 37 | 0.0589 | 4 |
| 79.612 | Fe I | 828 | 0.3110 | 3 | 89.471 | Cr I | | 2.2940 | 1,2 |
| 80.142 | Fe I | 515 | 0.0964 | 3 | 89.741 | Fe I | 2 | 0.0004 | 3 |
| 80.600 | Ti I | 146 | 0.3090 | 1,2 | 90.081 | Mn I | 22 | 1.0980 | 1,2 |
| 81.129 | Mg II | 4 | 3.0200 | 8 | 90.084 | Fe I | 469 | 0.1780 | 3 |
| 81.261 | Ti I | 146 | 2.7580 | 1,2 | 90.773 | Fe I | 974 | 0.6580 | 3 |
| 81.327 | Mg II | 4 | 5.7765 | 8 | 91.401 | Fe II | 37 | 0.0814 | 4 |
| 82.171 | Fe I | 2 | 0.0014 | 3 | 92.312 | Cr I | 197 | 2.1870 | 1,2 |

Table 7

Sources of gf values.

| Number | Source |
|---|---|
| 1 | Corliss and Bozman (1962) |
| 2 | Allen and Corliss (1963) |
| 3 | Corliss and Tech (1968) |
| 4 | Warner (1967) |
| 5 | Estimated from line intensities in multiplet |
| 6 | Wares (1970) |
| 7 | Baschek, Kegel, and Traving (1963) |
| 8 | Groth (1961) |
| 9 | Hill and King (1951) |

is much larger than that in the product gf times abundance. In general, most investigators have decreased the gf values and increased the abundances. Therefore we expect that future adjustments of the oscillator strengths may alter the details of our results, but they probably will not change the general features significantly since none of the features in the convolved spectra depend solely on one line.

## D. Instrumental Profile

After the synthetic spectra had been calculated, they were convolved with a "standard" instrumental profile in order to simulate the appearance of low dispersion spectra. We adopted a Gaussian instrumental profile characterized by a dispersion of 0.60 angstroms after studying density tracings of classification spectra taken at Yerkes Observatory by Dr. Anne P. Cowley. The adopted half width is probably a lower limit. Calculations have shown that our qualitative results are not very sensitive to the adopted instrumental profile. However, a smaller profile can be ruled out because it would give greater resolution than is observed on the plates.

Figures 1-3 show examples of the synthetic and convolved spectra for each spectral region. The major contributor to each line is identified below the lines in the synthetic spectra.

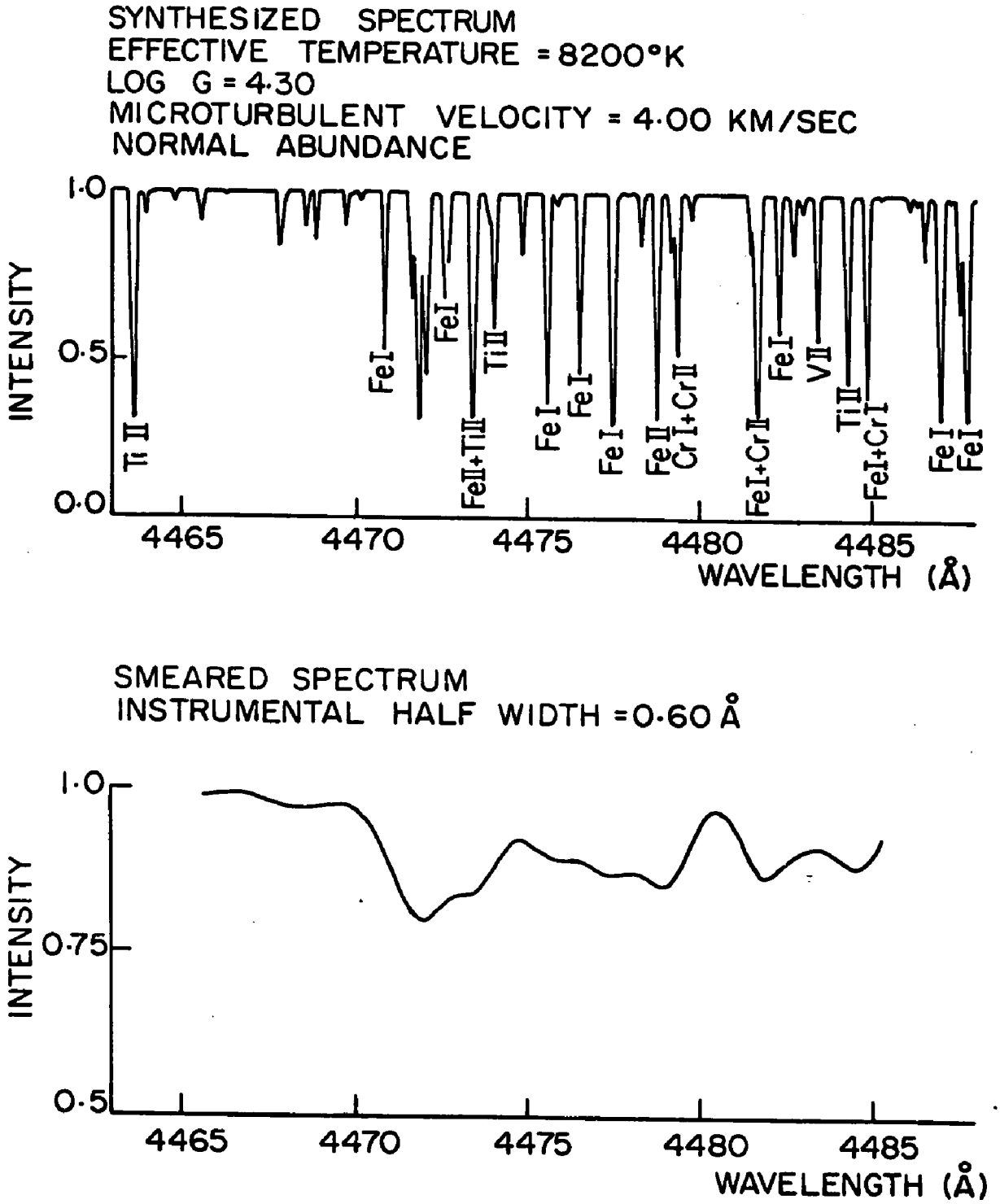



Figure 1. Example of synthetic and convolved synthetic spectra for the λλ4172-78 region.

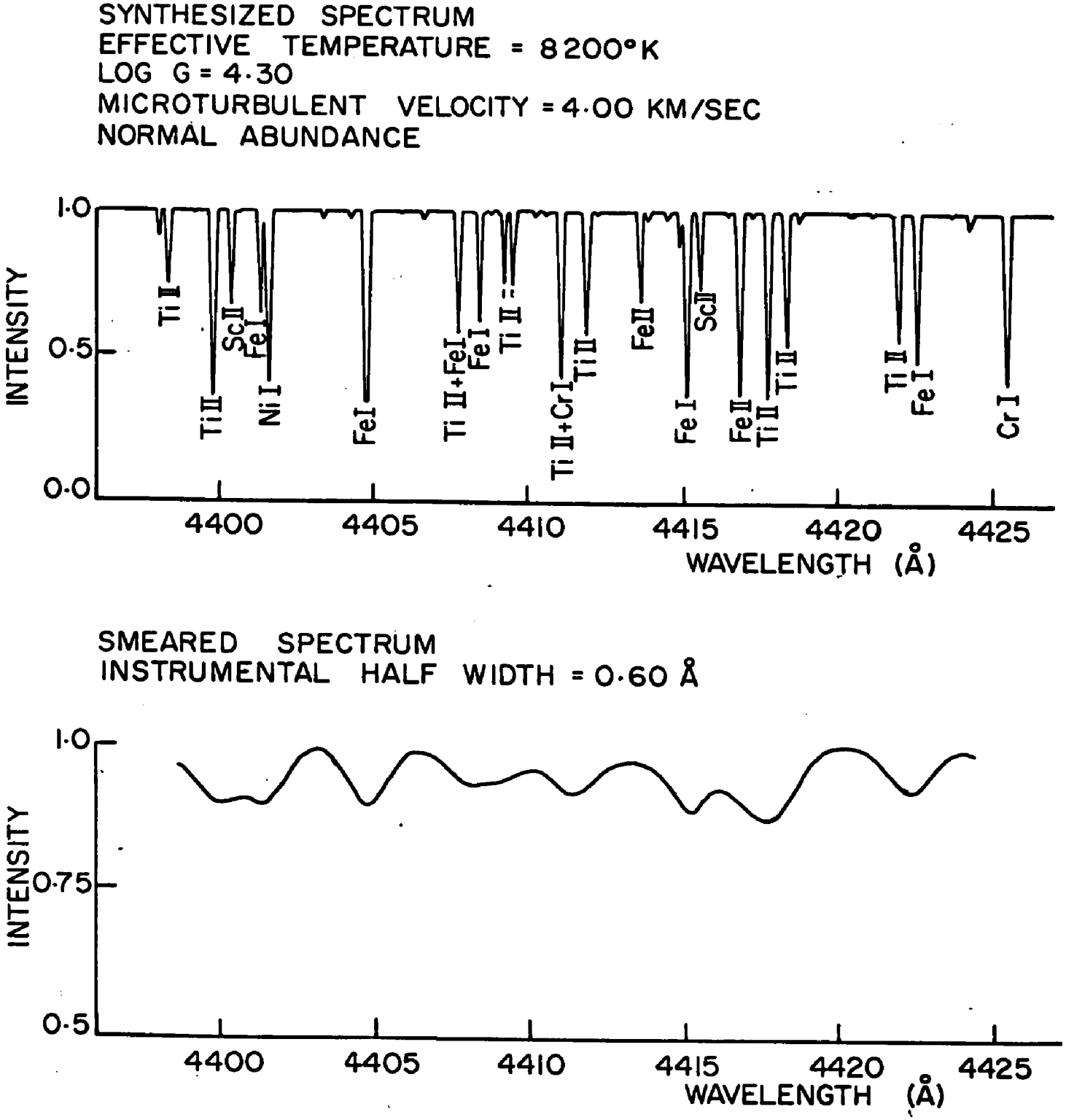



Figure 2. Example of synthetic and convolved synthetic spectra for the λ4417 region.

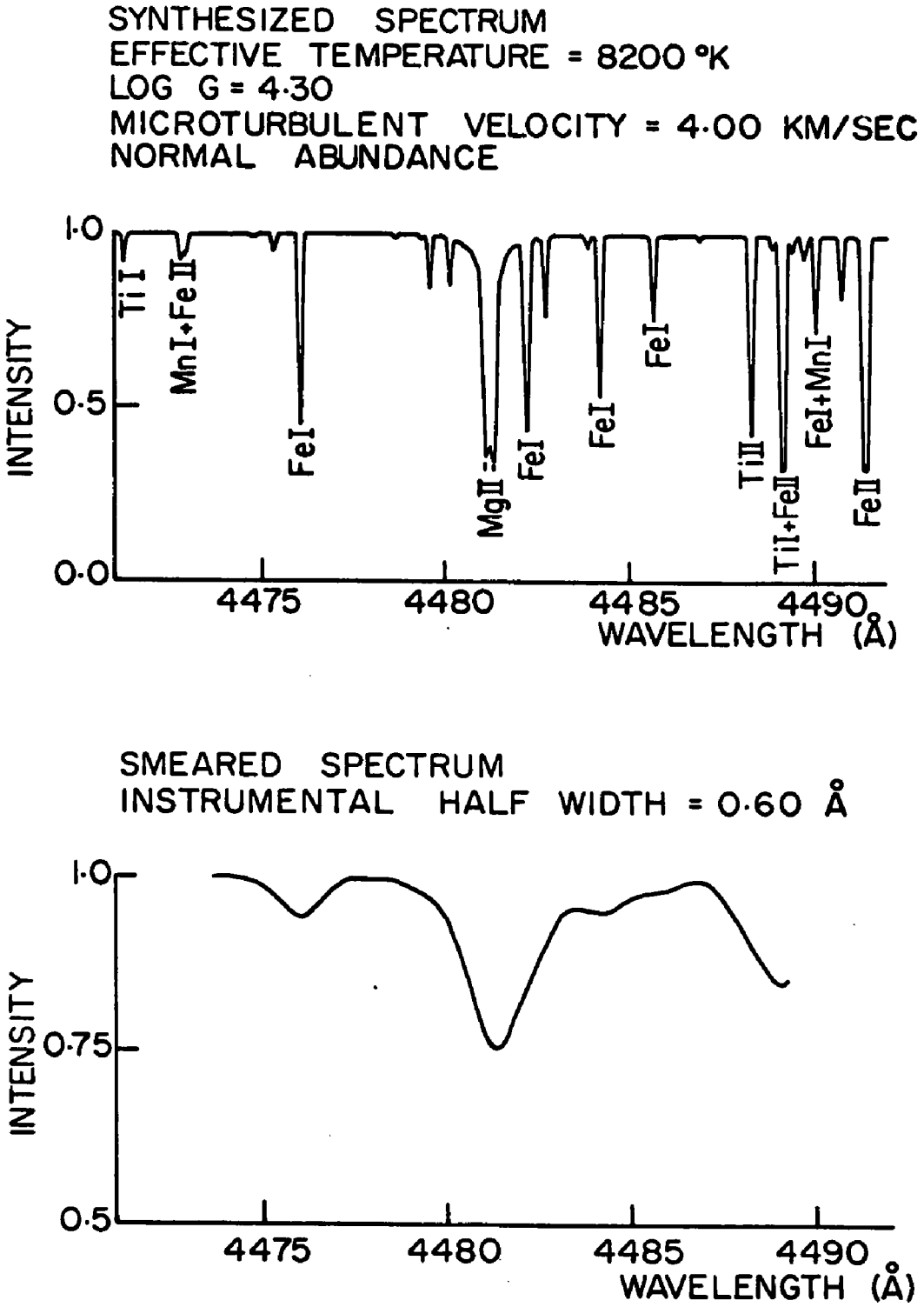



Figure 3. Example of synthetic and convolved synthetic spectra for the λ4481 region.

## IV. RESULTS

The first set of synthetic spectra was calculated by holding the microturbulence constant and allowing the surface gravity to vary from log g = 4.3 to log g = 2.5. Solar abundances were assumed. The results of these calculations for a temperature of 8200°K are shown in Figure 4. Notice that λ4481 is almost entirely insensitive to changes in log g, and that λ4172 is only slightly sensitive. The features at λ4417 and λ4178 show definite increases in strength with decreasing surface gravity. Thus the changes in the two ratios, λ4417: λ4481 and λ4178: λ4172, are qualitatively the same as are observed in low dispersion spectra. However, the changes are smaller than one might expect from a visual inspection of low dispersion spectra.

If a second set of synthetic spectra are calculated as above except that the microturbulence is allowed to increase with decreasing surface gravity, then the behavior shown in Figure 4 is duplicated, but the changes in the individual features are amplified considerably. The results shown in Figure 5 are more in line with the visual estimates of the strengths of these features. Similar calculations were also made at 6800°K, so that our synthetic spectra span a range of spectral type of roughly A6 to F3. The calculations indicate that the behavior of these classification features does not

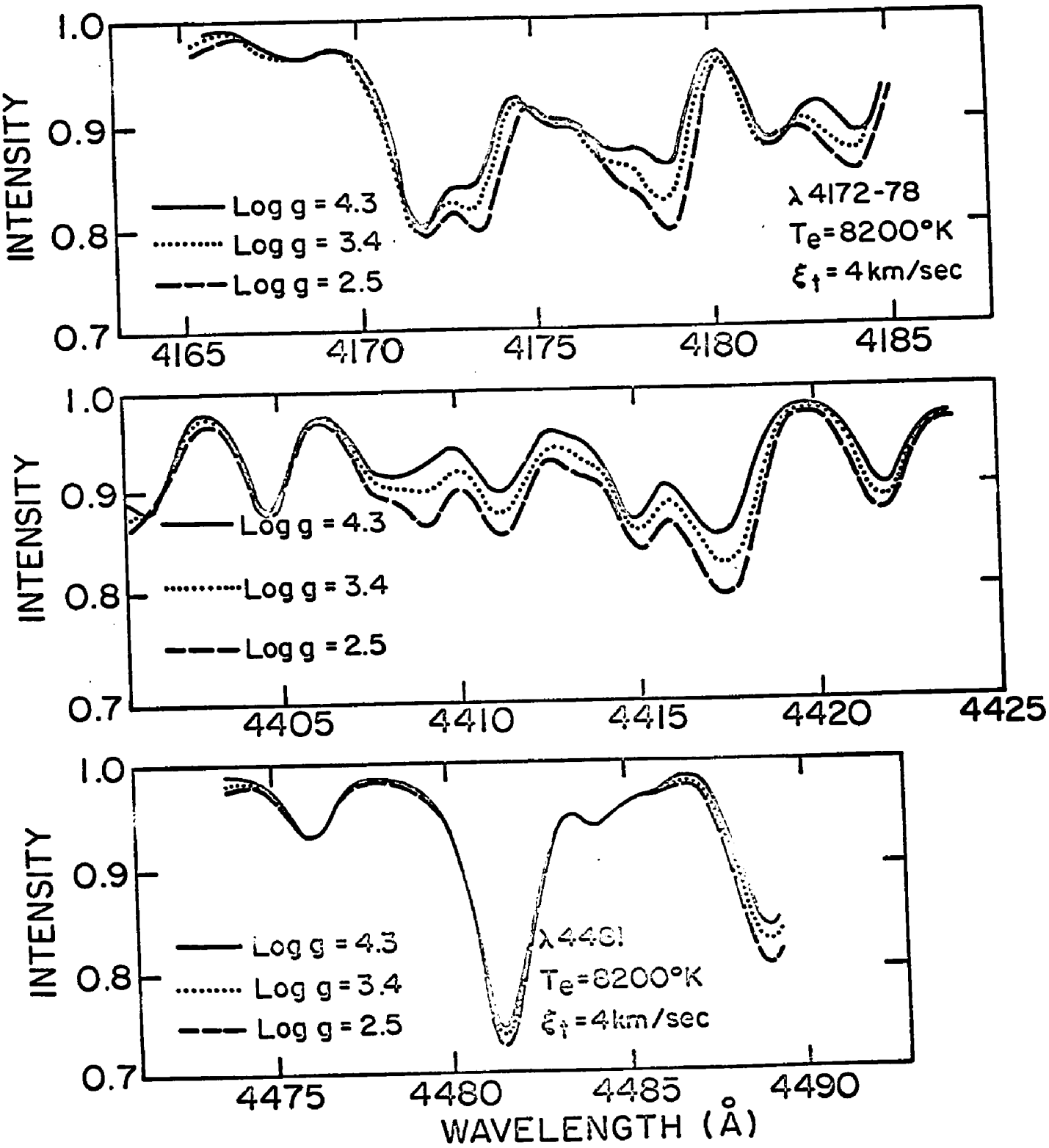



Figure 4. Convolved spectra computed for solar abundances and varying surface gravity. The microturbulent velocity is the same for all surface gravities.

**Figure 5.** Convolved spectra computed for solar abundances and varying surface gravity and microturbulence. These spectra were adopted as the "standards" for each surface gravity. The surface gravities correspond roughly to MK luminosity classes V, III, and II.

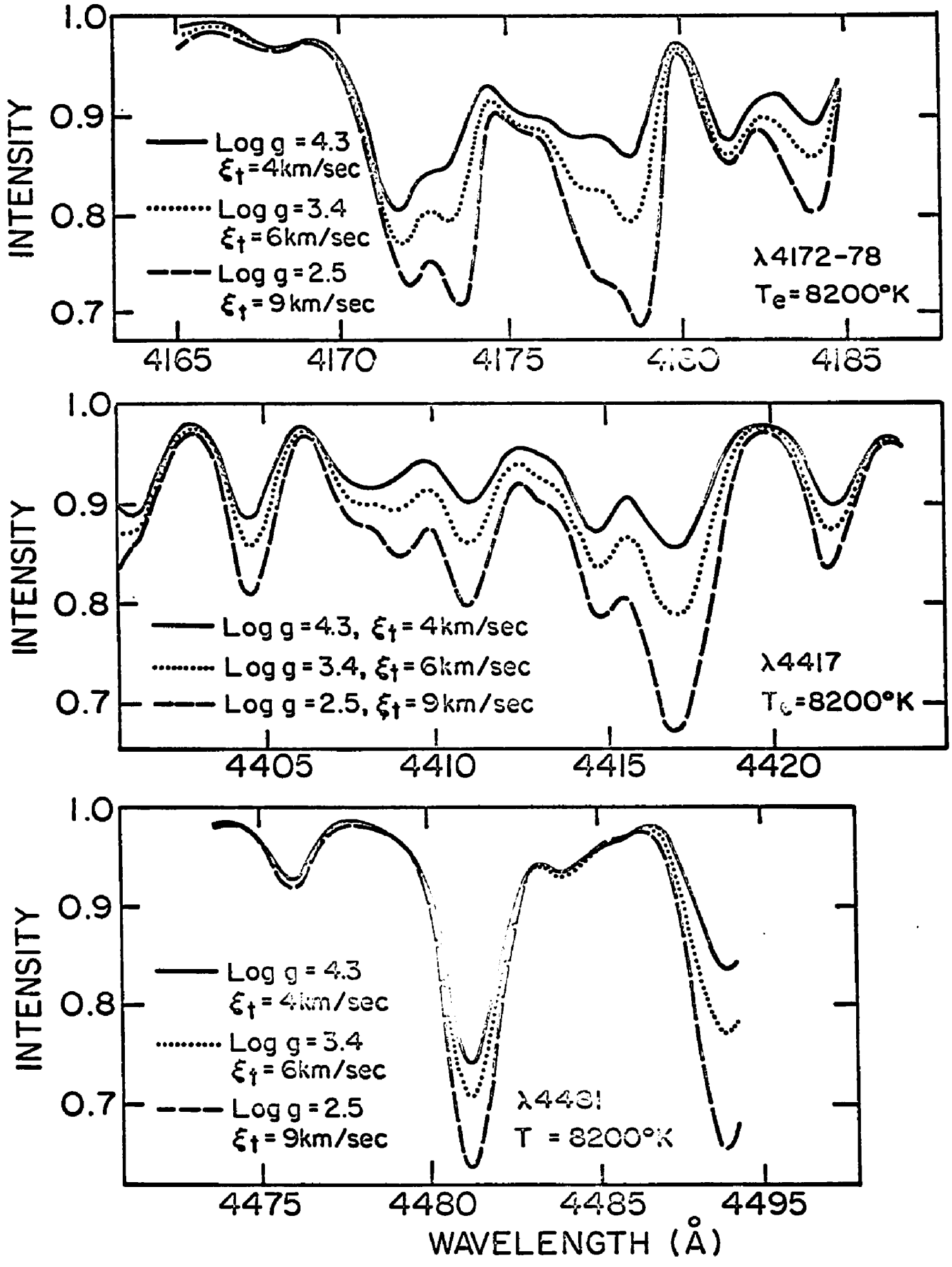

1.0
0.9
0.8
0.7
INTENSITY
Log g = 4.3
ξt = 4km/sec
Log g = 3.4
ξt = 6km/sec
Log g = 2.5
ξt = 9km/sec
λ4172-78
Te = 8200°K
4165
4170
4175
4180
4185
Log g = 4.3, ξt = 4km/sec
Log g = 3.4, ξt = 6km/sec
Log g = 2.5, ξt = 9km/sec
λ4417
Te = 8200°K
4405
4410
4415
4420
Log g = 4.3
ξt = 4km/sec
Log g = 3.4
ξt = 6km/sec
Log g = 2.5
ξt = 9km/sec
λ4481
T = 8200°K
4475
4480
4485
4495
WAVELENGTH (Å)

Figure 5.

change in any fundamental way over this range of spectral types.

Notice by comparing Figures 4 and 5 that the ratio λ4178:λ4172 is not changed significantly by the varying microturbulence, but the ratio λ4417:λ4481 is increased by increasing microturbulence. The adopted microturbulences for the dwarf surface gravities were taken from Chaffee (1970). We decided to increment the microturbulence 2 km/sec between log g = 4.3 and 3.4 and 3 km/sec between log g = 3.4 and 2.5 largely because λ4417, which we had already found to be microturbulence sensitive, showed a greater change on photographic plates between luminosity classes III and II than between classes V and III. Models were tried with different microturbulences than these, but we found that change in microturbulence with surface gravity was more critical than the values adopted at any one surface gravity. However, the near invisibility of the λ4417 feature in dwarf spectra probably argues against a microturbulence much higher than 4 km/sec at an effective temperature of 8200°K.

From the results above we might expect that if there is a large range of microturbulence at a given temperature and surface gravity, this could lead to classification ambiguities. In Figure 6 we see that this would be the case if only the ratio λ4417:λ4481 were used. We have already pointed out that

**Figure 6.** Convolved spectra showing the effect of varying the microturbulence at constant surface gravity for stars with solar abundances. The dotted line is the "standard" spectrum for a luminosity class III star. Note that a luminosity class III star with low microturbulence could be confused with an Am star (cf. Figure 7).

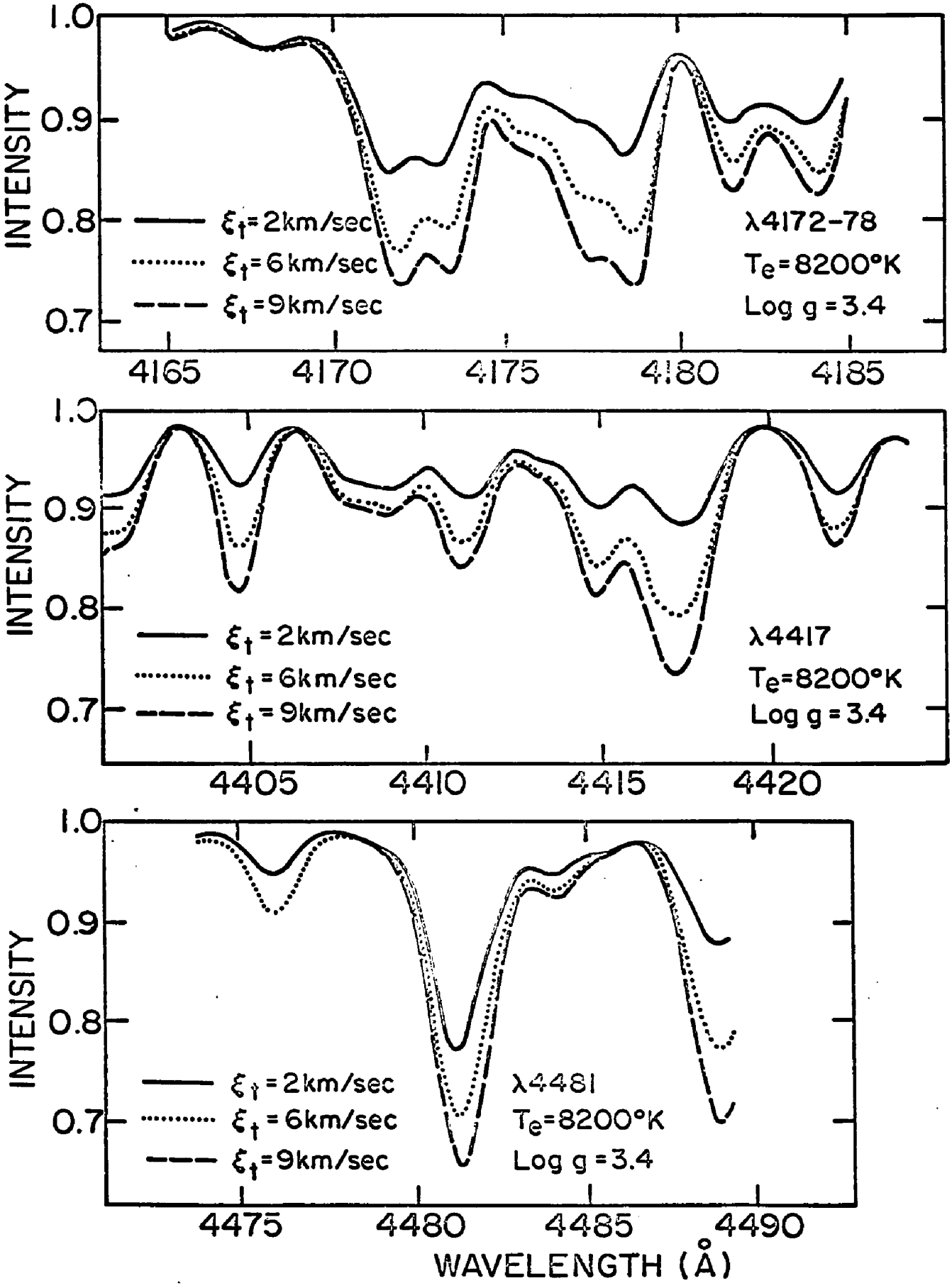

1.0
0.9
0.8
0.7
INTENSITY
$\xi_t$=2km/sec
$\xi_t$=6km/sec
$\xi_t$=9km/sec
λ4172-78
Te=8200°K
Log g=3.4
4165
4170
4175
4180
4185
1.0
0.9
0.8
0.7
INTENSITY
$\xi_t$=2km/sec
$\xi_t$=6km/sec
$\xi_t$=9km/sec
λ4417
Te=8200°K
Log g=3.4
4405
4410
4415
4420
1.0
0.9
0.8
0.7
INTENSITY
$\xi_t$=2km/sec
$\xi_t$=6km/sec
$\xi_t$=9km/sec
λ4481
Te=8200°K
Log g=3.4
4475
4480
4485
4490
WAVELENGTH (Å)

Figure 6.

the ratio λ4178:λ4172 is only slightly affected by microturbulence so that classifications based on this feature will not be affected. At spectral types later than F0 nearly the only distinguishing feature of Am stars is the non-enhancement of λ4417. Thus, a luminosity class III star with low microturbulence could be mistaken for an Am or weak Am star (compare Figure 6 with the metallic star's spectrum in Figure 7).

The results of the calculations for metallic abundances are shown in Figure 7. We found that a star with log g = 4.3, $\xi_t$ = 4 km/sec best simulated the observed features of Am stars seen at low dispersion. In Figure 7 the spectrum for such a star is compared with spectra for a dwarf and a giant star with solar abundances. The ratio of λ4178:λ4172 is not as strongly enhanced in the Am spectrum as might be expected, but the λ4178 feature appears as a sharp line rather than the more diffuse feature seen in the other spectra. This may account for the observed enhancement in the low dispersion spectra of Am stars. This sharp feature is due to a Cr I line at λ4179.257 and a Cr II line at λ4179.43. They are strengthened relative to the iron lines, which dominate this region, because the chromium abundance in Am stars is enhanced more than the iron abundance.

The situation at λ4417 is more well-defined. We find that this feature is only slightly enhanced in the Am

Figure 7. The convolved synthetic spectrum for an Am star compared with those for a dwarf and a giant star with solar abundances. Compare the changes in the computed lines with the effects described in section II.

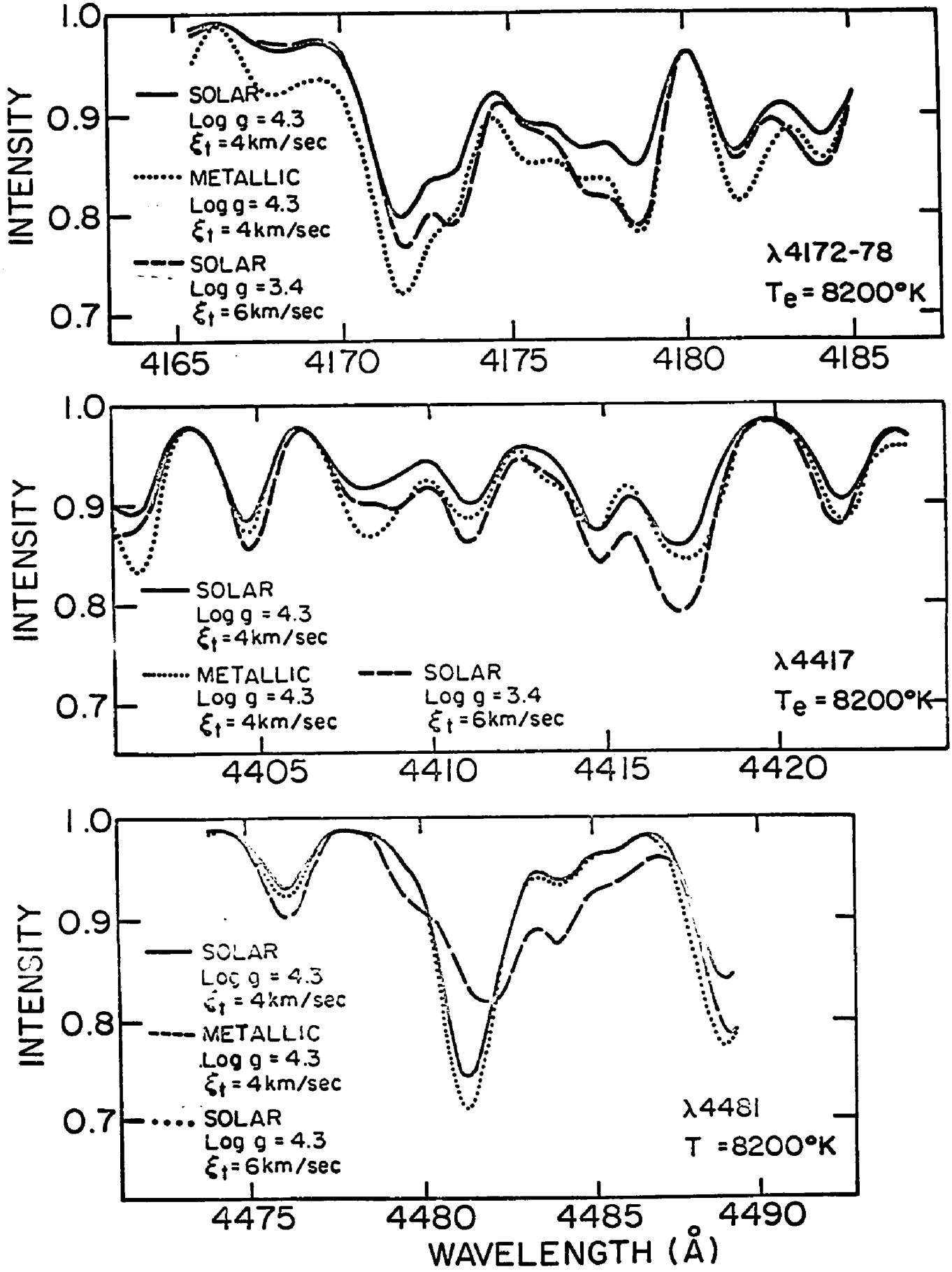

INTENSITY
1.0
0.9
0.8
0.7
SOLAR
Log g = 4.3
ξt = 4km/sec
METALLIC
Log g = 4.3
ξt = 4km/sec
SOLAR
Log g = 3.4
ξt = 6km/sec
λ4172-78
Te = 8200°K
4165
4170
4175
4180
4185
INTENSITY
1.0
0.9
0.8
0.7
SOLAR
Log g = 4.3
ξt = 4km/sec
METALLIC
Log g = 4.3
ξt = 4km/sec
SOLAR
Log g = 3.4
ξt = 6km/sec
λ4417
Te = 8200°K
4405
4410
4415
4420
INTENSITY
1.0
0.9
0.8
0.7
SOLAR
Log g = 4.3
ξt = 4km/sec
METALLIC
Log g = 4.3
ξt = 4km/sec
SOLAR
Log g = 4.3
ξt = 6km/sec
λ4481
T = 8200°K
4475
4480
4485
4490
WAVELENGTH (Å)

Figure 7.

spectrum. This is due to a small overabundance of titanium, which dominates the feature, and the presence of one line of Fe II. The enhancement is even less at 6800°K. λ4417 is barely visible in the spectra of normal dwarf stars, and the very small enhancement found for the Am star is not likely to increase the visibility of the line significantly. If this small enhancement is enough to increase the visibility, then it would be necessary to argue that the titanium abundance (and perhaps that of iron as well) is not as high as that found by V'ant Veer-Menneret. This would be consistent with the results of Conti (1965) and Greenstein (1948), who found that titanium was slightly under-abundant in Am stars. Their abundances would not alter our result for the λ4178:λ4172 ratio.

The relative enhancement of the λ4178:λ4172 ratio compared to the λ4417:λ4481 ratio is amplified by the positions of the absorption lines on the curve of growth. The titanium lines at λ4417 are just coming on to the left-hand part of the flat portion of the curve of growth. Therefore it would take a considerable increase in the titanium abundance to boost the strength of the λ4417 feature very much. The iron and chromium lines at λ4178 are much stronger and lie near the start of the damping part of the curve of growth. Hence they are much more sensitive to increases in abundance than are the titanium lines at λ4417.

## V. DISCUSSION

We have shown that the "luminosity-sensitive" ratio λ4417:λ4481 is at least as sensitive to microturbulence as it is to surface gravity. Its use as an absolute magnitude indicator thus depends upon the correlation between luminosity and microturbulence. We have already shown how deviations from such a correlation could cause the luminosity class to be misidentified for normal stars or cause normal giants to be classified as Am or weak Am stars. It is also possible that Am stars with high microturbulent velocities could be classified as normal giants (see Figure 8).

There is not enough data available at the present time to be able to say whether there is a large scatter in microturbulence for a given spectral type and luminosity class. The present results suggest that the scatter cannot be very large. Otherwise λ4417 would not have been as successful a luminosity indicator as it has been. Chaffee (1970) has found little scatter for dwarf stars, but his data is limited in the spectral range A0 to F5. His results have been confirmed by Myron Smith (private communication). Hack (1970) has compiled a comprehensive list of microturbulence determinations. She finds that there is considerable evidence for large variations in microturbulence at a given spectral type and luminosity class for the A stars. However, the

**Figure 8.** The convolved spectrum for an Am star with high microturbulence compared with a giant star with solar abundances. Such an Am star would be called a normal giant or sub-giant unless it possessed distinguishing characteristics other than the ones computed here. Late-type Am stars usually do not have other distinguishing features since the Ca II K line has become saturated.

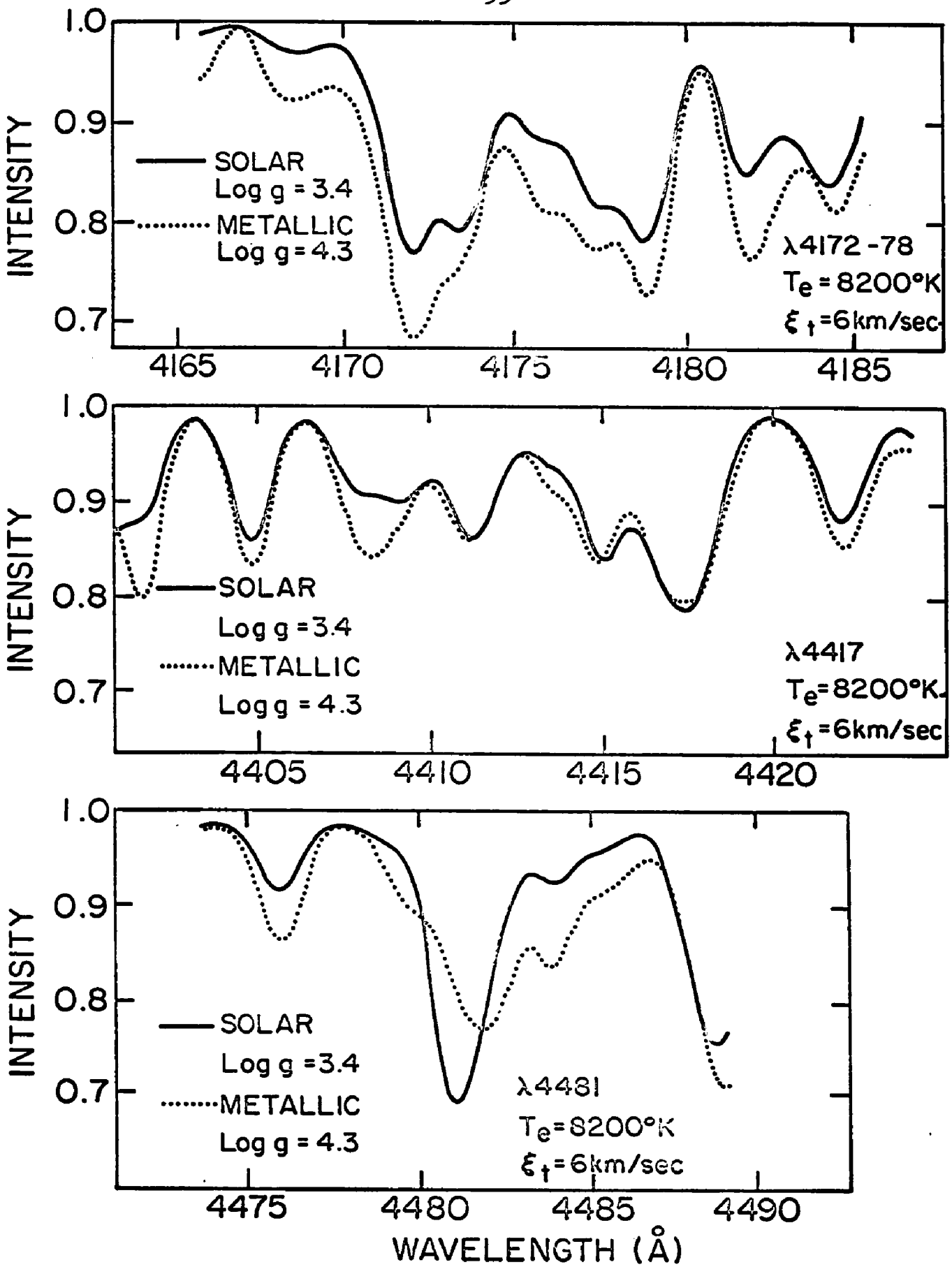

1.0
0.9
0.8
0.7
INTENSITY
SOLAR
Log g = 3.4
METALLIC
Log g = 4.3
λ4172-78
Te = 8200°K
ξt = 6km/sec
4165
4170
4175
4180
4185
1.0
0.9
0.8
0.7
INTENSITY
SOLAR
Log g = 3.4
METALLIC
Log g = 4.3
λ4417
Te = 8200°K
ξt = 6km/sec
4405
4410
4415
4420
1.0
0.9
0.8
0.7
INTENSITY
SOLAR
Log g = 3.4
METALLIC
Log g = 4.3
λ4481
Te = 8200°K
ξt = 6km/sec
4475
4480
4485
4490
WAVELENGTH (Å)

Figure 8.

variation of results for a single object among different investigators (±1.5 km/sec according to Hack) is large enough to mask the correlation that we suggest. Because of the influence that microturbulence can have on spectral classification and intermediate band photometry (Conti and Deutsch 1966) it is extremely important to study its behavior as a function of spectral type and luminosity class.

The role of element abundance variations in A and F star spectra may be even more important than that of microturbulence. We have attributed the "anomalous luminosity effect" between the ratios λ4178:λ4172 and λ4417:λ4481 in Am spectra to differential abundance enhancements among iron, chromium, and titanium. That is, the enhancement of one spectral feature over another is attributed to the abundance of an element whose lines dominate one region being enhanced more in Am stars than the abundance of an element whose lines dominate another region. Notice that since the differential enhancement is between stars and not between elements, our result is insensitive to the system of oscillator strengths.

The Am stars are known to be an inhomogeneous group and the A and F stars might also be somewhat inhomogeneous in their element abundances. Such inhomogeneities could cause classification ambiguities and may in fact be responsible for the numerous "anomalous luminosity effects" found by Barry

(1970) in his ultraviolet classification work on A and F stars. Considerably more high dispersion work on these stars is needed to determine the nature and range of the abundance variations that exist.

We have found that considerable insight can be obtained in the interpretation of low-dispersion spectra of A and F stars by comparing our theoretical calculations with results from the visual inspection of photographic plates. However, this approach is limited by our inability to define what the eye "sees". This can best be seen in Figure 7 where the Am spectrum is compared with those of a normal giant and a normal dwarf. In comparing these results with visually classified spectra it appears that the eye is sensitive to a variety of changes. Note that the primary change at λ4178 is in the line width. At λ4417 both the line depth and equivalent width change. At λ4481 the line depth and shape change, but the equivalent width remains approximately constant. The feature is not observed to change much on photographic plates. Clearly the value of computations such as the ones described here will be increased considerably when used in conjunction with quantitative spectrophotometry.

This work demonstrates that spectral classification is a very powerful tool for the study of stellar atmospheres. Its usefulness is somewhat limited by our present lack of

knowledge of the absolute values and ranges of parameters such as microturbulence and abundances as a function of spectral type and luminosity class. There is also a need for studies correlating visually observed features in spectra with the theoretical calculations. Work, such as that of Barry (1970), is needed to find more low-dispersion spectral features that can be correlated with the physical parameters of a stellar atmosphere. Once such features are found, they can be calibrated by the techniques described here.

## REFERENCES


Allen, C. W., and Corliss, C. H. 1963, M.N.R.A.S., 126, 37.

Barry, D. C. 1970, Ap. J. Suppl., 19, 281.

Baschek, B., Kegel, W. H., and Traving, G. 1963, Zs. f. Ap., 56, 282.

Bode, G. 1965, Die kontinuierliche Absorption von Sternatmospharen in Abhangigkeit von Druck, Temperatur, und Elementhaufigkeiten (Kiel: Universitat Kiel).

Bolton, C. T. 1970, Ap. J., 161, 1187.

Bridges, J. M., and Wiese, W. L. 1970, Ap. J. Lett., 161, L71.

Chaffee, F. 1970, Astron. and Ap., 4, 291.

Conti, P. S. 1965, Ap. J. Suppl., 11, 47.

Conti, P. S., and Deutsch, A. J. 1966, Ap. J., 145, 742.

Corliss, C. H., and Bozman, W. R. 1962, N.B.S. Monograph, No. 53.

Corliss, C. H., and Tech, J. L. 1968, N.B.S. Monograph, No. 108.

Cowley, A. P., Cowley, C. R., Jaschek, M., and Jaschek, C. 1969, A.J., 74, 375.

Cowley, C. R. 1970, The Theory of Stellar Spectra (New York: Gordon and Breach).

Cowley, C. R., Elste, G. H. E., and Allen, R. H. 1969, Ap. J., 158, 1177.

Elste, G. H. E. 1964, Proceedings First Harvard-Smithsonian Conference on Stellar Atmospheres, p. 11.

Evans, J. C. 1966, thesis, University of Michigan.

Greenstein, J. 1948, Ap. J., 107, 151.

Griem, H. R. 1964, Plasma Spectroscopy (New York: McGraw-Hill).

Griem, H. R. 1968, Phys. Rev., 165, 258.

Groth, H. G. 1961, Zs. f. Ap., 51, 231.

Hack, M. 1970 Sky and Tel., 40, 143.

Hill, A. J., and King, R. B. 1951, J.O.S.A., 41, 315.

Hiltner, W. A. 1945, Ap. J., 102, 438.

Hiltner, W. A., and Williams, R. C. 1946, Photometric Atlas of Stellar Spectra (Ann Arbor: University of Michigan Press).

Hobbs, L. M., and Cowley, C. R. 1968, Ap. J., 153, 909.

Mihalas, D. 1966, Ap. J. Suppl., 13, 1.

Moore, C. E. 1945, Contr. Princeton Univ. Obs., No. 20.

Morgan, W. W., Keenan, P. C., and Kellman, E. 1943, An Atlas of Stellar Spectra (Chicago: University of Chicago Press).

Muller, E. A. 1968, Origin and Distribution of the Elements, ed. L. H. Ahrens (Oxford: Pergamon Press). p. 155.

Takens, R. J. 1970. Astron. and Ap., 5, 244.

Unsold, A. 1955, Physik der Sternatmospharen (Berlin: Springer).

V'ant Veer-Menneret, C. 1963, Ann. D'Ap., 26, 289.

Wares, G. 1970, Bull. A.A.S., in press.

Warner, B. 1967, Mem. R.A.S., 70, 167.

Wright, K. O. 1964, Pub. D.A.O., 7, no. 7.