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THE NITROGEN ABUNDANCE OF THE VERY METAL-POOR STAR HD 122563

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ABSTRACT

The nitrogen abundance for the very metal-poor giant HD 122563 has been determined, using new spectroscopic plate data of the CH, NH, and CN molecular bands and a spectrum synthesis analysis. The results indicate that nitrogen is overabundant by a factor of 15 relative to iron, while carbon is underabundant by a factor of 3. Account has been taken of the influence of the unknown oxygen abundance on the carbon equilibrium.
Subject headings: abundances, stellar — late-type stars — stars, individual — weak-line stars

I. INTRODUCTION

Abundance determinations of metal-deficient stars have become important in recent years because such studies have helped to increase our understanding of the chemical evolution of the Galaxy. Different theories about possible nucleosynthesis sites predict different chemical anomalies, which can be tested with abundance surveys. Metal-deficient stars are important in this work because they have been formed in relatively unevolved regions of space. Since their atmospheres reflect the products of (hopefully) only a few nucleosynthesis events, these stars can show most clearly the effects of heavy-element generation. Two main sites have been proposed for nucleosynthesis. Wagoner (1969) proposed that the abundances of elements seen in stellar atmospheres could have been produced in explosions of supermassive objects, while Arnett (1969) and others have attempted to use ordinary stars as nucleosynthesis sites. These two theories predict roughly the same element-abundance ratios, in part because models were chosen which produced reasonable abundances. Wagoner's (1969) models, however, synthesize nitrogen in about the same quantity as carbon and oxygen, while some of Arnett's simpler models find nitrogen virtually absent. Therefore, nitrogen-abundance studies could provide a test of these rival theories. This paper describes such an analysis.

The extremely metal-deficient giant HD 122563 has been studied extensively, mainly because it is the only very metal-poor star bright enough to permit the use of high-dispersion spectrograms. The first detailed analysis was made by Wallerstein *et al.* (1963). A careful reanalysis of HD 122563, using the equivalent widths of Wallerstein *et al.* (1963) was performed by Pagel (1965). He determined a metal to hydrogen ratio of [Fe/H] = -2.55 ± 0.25, where the standard notation

$$[\text{element/H}] \equiv \log_{10}(\text{element/H})_{\text{star}} - \log_{10}(\text{element/H})_{\text{Sun}}$$

will apply throughout this article. No attempt was made in either one of these analyses to determine a nitrogen abundance. In order to obtain any information on nitrogen using blue spectral plates, one must deal with the molecular CN bands. Since carbon and nitrogen are predominantly in the free atomic states, the intensities of the CN bands depend roughly on the product of the abundances of carbon and nitrogen. Therefore, in metal-poor G-type stars, the band intensities decrease approximately as the square of the metal deficiency. Ball and Pagel (1967) did obtain new spectra of the 4000 Å spectral region of HD 122563 with the intent of making a carbon and nitrogen analysis. Using several unblended CH features, they determined a carbon abundance of [C/Fe] = −0.9 ± 0.5 if [O/Fe] = 0. (The large uncertainty here stems mainly from large uncertainties in the physical parameters [P_g], [P_e] and $\Delta\theta$.) They set only an upper limit for nitrogen, because the 4215 Å CN band was completely invisible on their plates. A final reanalysis by Wolffram (1972) used a model-atmosphere approach, rather than the previously used differential curve-of-growth method. This analysis included a determination of the carbon abundance ([C/Fe] = −0.42 ± 0.40, and [Fe/H] = −2.72 ± 0.30), but no nitrogen data.

Since no solid answer is available for nitrogen, it was decided to undertake a new spectroscopic analysis of HD 122563, obtaining plates of the CH 4300 Å band, the CN 3883 Å and 3871 Å bands, and the NH 3360 Å and 3370 Å bands. At the temperatures we are dealing with here, around 4000° K, oxygen does not enter into the nitrogen equilibrium, but enters in the carbon equilibrium through formation of CO molecules. The oxygen abundance is very difficult to determine, and has not been ascertained for HD 122563. The nitrogen equilibrium is affected slightly by the formation of N_2 molecules. Therefore, the obvious advantage of using the NH bands rather than the CN bands is that the NH band intensities depend only on the nitrogen abundance, and not on an unknown oxygen parameter. A major drawback is the difficulty in finding unblended NH features. This presents no severe obstacle in a spectrum synthesis approach. To the author's knowledge, no previous stellar abundance study has ever made use of the NH bands.

II. THE OBSERVATIONS AND REDUCTIONS

The new plates were all obtained at McDonald Observatory, using the coudé spectrograph of the 201-cm Struve Reflector, with calibration plates simultaneously exposed on a tube sensitometer. The plate data is listed in table 1. The spectrum and calibration plates were traced on the microdensitometer of the Astronomy Department. This microdensitometer has a digital output, which allowed the data from different plates to be added together once conversions from density to intensity and plate position to wavelength had been made. In this manner the plate grain noise was reduced to some extent. A comparison was made between equivalent widths of lines from our tracings and the published equivalent widths of Wallerstein *et al.* (1963). Our equivalent widths appear to be larger by

$$\log W/\lambda = 0.07 \pm 0.03 .$$

This discrepancy is not a large one, and it is consistent with the findings of Wright (1966), who showed that equivalent widths tend to increase with decreasing dispersion.

TABLE 1

THE OBSERVATIONAL MATERIAL

Plate No.	Dispersion (Å mm^{-1})	Date	Emulsion	λ_c (Å)	useful λ range (Å)
7216.......	9	1971 February 16	baked IIa-0	4200	3700–4800
7444.......	9	1971 June 16	baked IIa-0	4200	3700–4800
7762.......	9	1972 April 6	baked IIa-0	3400	3250–3900
7770.......	9	1972 April 27	baked IIa-0	3400	3250–3900
7773.......	9	1972 April 29	baked IIa-0	3400	3250–3900

III. THE SPECTRUM SYNTHESIS PROGRAM

A spectrum synthesis program has been created for the purpose of matching observed stellar spectra. Given a model atmosphere, element abundances, and line parameters for all relevant lines in a given spectral region, this program will compute a set of line depths which can be compared to the observed stellar spectrum. The program assumes local thermodynamic equilibrium (LTE), and has Doppler and van der Waals line-broadening mechanisms included. In the remainder of this section we discuss the various input quantities for the program.

The model atmosphere was the one determined by Wolffram (1972). His flux-constant model assumes LTE, and has been corrected for effects of line blanketing and convection. The model parameters used were

$$T_e = 4600^\circ \pm 150^\circ\,\mathrm{K}\,; \qquad \log g = 1.2 \pm 0.4\,; \qquad [M/\mathrm{H}] = -2.75 \pm 0.3\,.$$

For the purpose of this study the atomic abundances derived by Wolffram (1972) have been adopted. The spectrum synthesis program is set up to accept model-atmosphere parameters at a certain reference wavelength. Wolffram's (1972) atmosphere is in the form of temperature versus a Rosseland mean optical depth. However, the model atmosphere program ATLAS, when given Wolffram's model parameters and a reference wavelength of 5000 Å, produced a model almost identical to that of Wolffram, so this wavelength was adopted as the reference wavelength.

Parameters for the CH $A\,^2\Delta - X\,^2\Pi$ band system were obtained from the following sources. Wavelengths of the lines in the region 4290–4315 Å for the 0–0, 1–1, and 2–2 bands were taken from the solar line identifications of Moore and Broida (1959). Line strengths and excitation potentials were obtained from tables computed by Dr. David L. Lambert (unpublished). Band oscillator strengths derived from radiative lifetime measurements have been published by several authors. A summary will appear in Lambert and Mallia (1973), who give

$$f_{0-0} = (7.50 \pm 0.8) \times 10^{-3}\,; f_{1-1} = (7.44 \pm 0.7) \times 10^{-3}\,; f_{2-2} = (7.41 \pm 0.7) \times 10^{-3}\,.$$

For the CN violet ($B\,^2\Sigma^+ - X\,^2\Sigma^+$) system, wavelengths, and excitation potentials were calculated using the formulas of Brocklehurst *et al.* (1972). Liszt and Hesser (1970) give the following band oscillator strengths:

$$f_{0-0} = (3.64 \pm 0.04) \times 10^{-2}\,; f_{1-1} = (3.08 \pm 0.3) \times 10^{-2}\,; f_{0-1} = (2.7 \pm 0.3) \times 10^{-3}\,.$$

Rotational line strengths were calculated from expressions given by Kovacs (1969). The dissociation energy of CN is not precisely known, but many recent authors (see Arnold and Nicholls 1972) give values close to 7.85 eV.

For the NH ($A\,^3\Pi_i - X\,^3\Sigma^-$) system we have adopted identifications and wavelengths from Dixon (1959) for the 0–0 band and from Murai and Shimauchi (1966) for the 1–1 band. Rotational constants from Murai and Shimauchi (1966) provided excitation potentials. The line strength formulas of Kovacs (1969) were used for these lines. Lambert and Mallia (1973) give the following oscillator strengths:

$$f_{0-0} = (7.70 \pm 0.8) \times 10^{-3}\,; \qquad f_{1-1} = (7.74 \pm 0.8) \times 10^{-3}\,.$$

The 2–2 band has been neglected, since no lines of this band have been positively identified in the solar spectrum, and examination of the tracings of the 0–0 and 1–1 bands of NH in HD 122563 indicated that if present at all, the 2–2 band should be weak.

The atomic "contaminating" lines selected are those appearing in the catalog of Fraunhofer lines (Moore, Minnaert, and Houtgast 1966). Oscillator strengths were computed for these lines through the use of a line analysis program, the Harvard-Smithsonian Reference Atmosphere (HSRA) of Gingerich *et al.* (1971), and the equivalent widths listed by Moore *et al.* (1966). It was assumed that the solar abundances and solar equivalent widths were exact, and the oscillator strengths were changed until the predicted equivalent widths matched the observed solar ones.

To test the quality of all the line parameters, the CN, CH, and NH bands were synthesized using the HSRA model atmosphere and compared to the solar atlases. Very reasonable agreement was obtained between the predicted and computed CH and NH spectra. The CN predicted intensities are much too strong when compared to the solar spectrum. If, instead of taking $D_{CN} = 7.85$, we use $D_{CN} = 7.55$, which is roughly the lower value found by some investigators, good agreement is obtained between computed and observed solar spectra. This may not be the complete answer to the discrepancy, but is one way in which it can be resolved. These calculations of solar CH, CN, and NH lines confirm the results of an independent study by Lambert and Mallia (1973).

IV. ANALYSIS OF HD 122563

Using the line parameters and model atmosphere described above, the CH, CN, and NH spectra were synthesized for several values of the carbon and nitrogen abundances, and an assumed oxygen deficiency equal to that of the metals. Since no data is available on the slit function of the coudé spectrograph of the Struve reflector, a crude smoothing procedure was used. Line depths were computed at every 0.02 Å in the spectrum, and a straight mean was taken of points up to 0.12 Å on either side of each wavelength step. Since the limiting resolution on the plate was roughly 0.20 Å, this was a reasonable number of spectrum points to average. One can see in the figures that this smoothing provided reasonable fits to the atomic line depths. The following paragraphs will describe the individual bands, and the abundance results are summarized in table 2.

a) NH

Figures 1 and 2 show the fits obtained for these bands. The best answer, $[N/H] = [Fe/H] + (1.2 \pm 0.10)$ represents a marked overabundance of nitrogen relative to the metals. In examining figure 1, one can see that the 0–0 band is not well matched at the band center. This band is fairly saturated at the center, and thus registered very weakly on the spectrograms taken. Very little weight was put on matching this portion of the spectrum. Individual 0–0 lines away from the band center and all of the 1–1 band are very sensitive to the abundance changes. The molecule N_2, the chief contributor to the nitrogen equilibrium, takes up less than 1 percent of the nitrogen at the temperatures and abundances with which we are dealing. It is worth noting here that the atomic lines are fitted in this heretofore untouched spectral region as well as they are in the regions of the CH and CN bands.

TABLE 2
ABUNDANCE RESULTS

Element	$\log (N_{el}/N_H)_{Sun}$	$\log (N_{el}/N_H)_{122563}$	$[N_{el}/N_H]$	$[N_{el}/N_{Fe}]$
C.............	−3.5	−6.6 ± 0.4	−3.1 ± 0.4	−0.4 ± 0.5
N.............	−4.1	−5.6 ± 0.4	−1.5 ± 0.4	+1.2 ± 0.5
O.............	−3.2	< −5.0	< −1.8	< +0.9
Fe............	−4.5	−7.2 ± 0.3	−2.7 ± 0.3	0.0

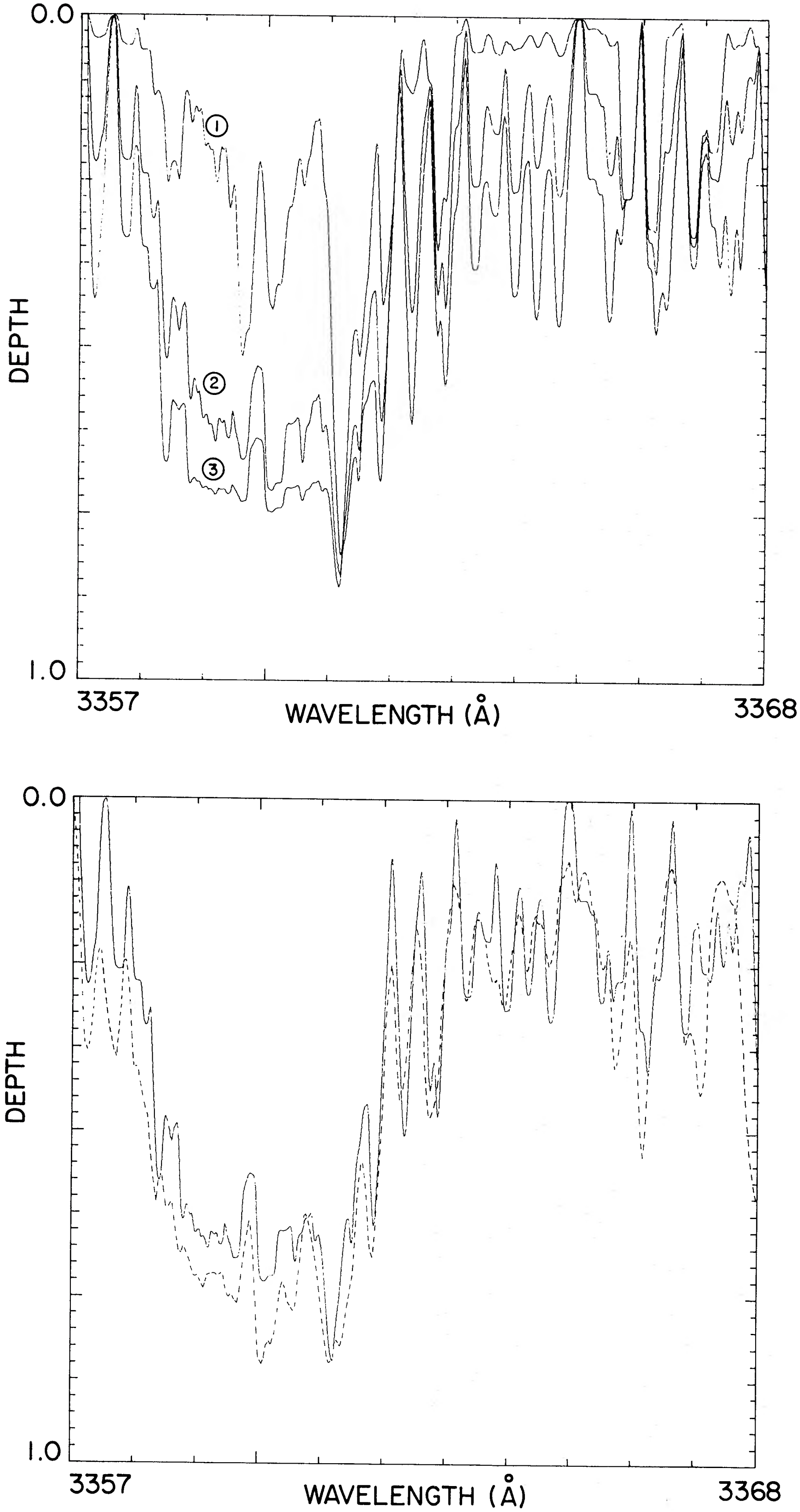

FIG. 1.—The NH 0–0 band. (*a*) (*top*) Synthetic spectra for (1) [N/H] = [Fe/H], (2) [N/H] = [Fe/H] + 1.0, and (3) [N/H] = [Fe/H] + 1.6. (*b*) (*bottom*) The solid line is the synthetic spectrum for [N/H] = [Fe/H] + 1.2. The broken line is the observed spectrum.

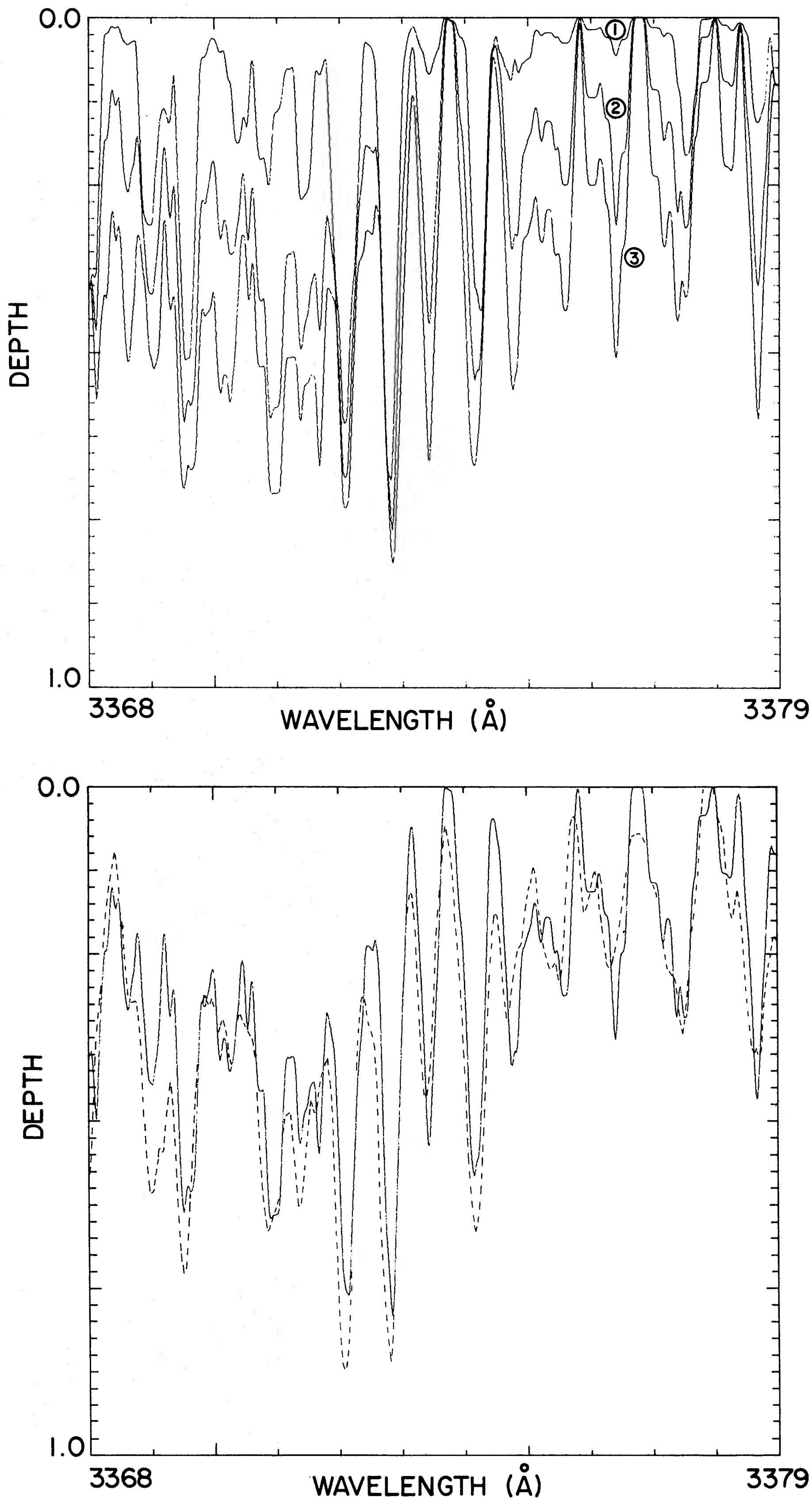

FIG. 2.—The NH 1–1 band. (*a*) (*top*) Synthetic spectra for (1) [N/H] = [Fe/H], (2) [N/H] = [Fe/H] + 1.0, and (3) [N/H] = [Fe/H] + 1.6; (*b*) (*bottom*) The solid line is the synthetic spectrum for [N/H] = [Fe/H] + 1.2. The broken line is the observed spectrum.

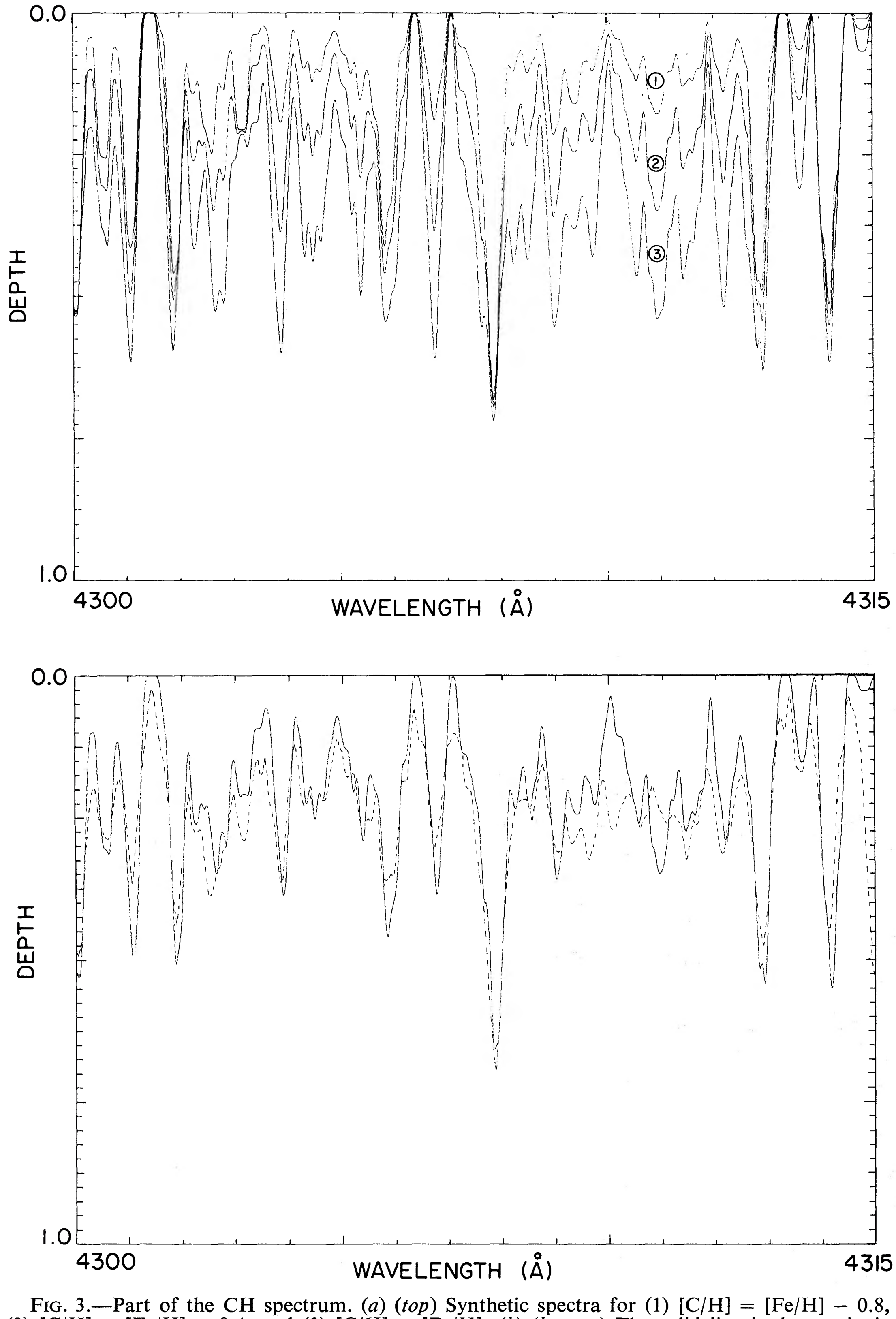

FIG. 3.—Part of the CH spectrum. (*a*) (*top*) Synthetic spectra for (1) [C/H] = [Fe/H] − 0.8, (2) [C/H] = [Fe/H] − 0.4, and (3) [C/H] = [Fe/H]; (*b*) (*bottom*) The solid line is the synthetic spectrum for [C/H] = [Fe/H] − 0.4. The broken line is the observed spectrum.

b) CH

As figure 3 shows, the best agreement between computed and observed spectra occurs (assuming [O/H] = [Fe/H]) for [C/H] = [Fe/H] $-(0.4 \pm 0.1)$. This confirms the result of Wolffram (1972), which was based on equivalent widths of individual lines, using different plate material. In tests on individual lines of CH, it was found that a decrease in the oxygen abundance produced a negligible effect on the CH equivalent widths, while an oxygen increase by a factor of 10 produced a 12 percent decrease in the equivalent widths. The effect then is quite small.

c) CN

These bands were used to confirm the results obtained from the CH and NH bands. Good agreement occurred for the 1–1 band if the abundances from the CH and NH bands were used with a dissociation energy of $D_{CN} = 7.55$, but not if $D_{CN} = 7.85$ (see fig. 4). This adjustment is identical with that required to match the solar spectrum. There are some strong atomic lines near the 0–0 bandhead which could not be accurately assigned oscillator strengths based on solar data. The reason for this is that in the solar spectrum the 0–0 band is so strong that one cannot measure the equivalent widths of the atomic contaminating lines with any great precision. These uncertainties render the 0–0 bandhead computations suspect. The line program was also used to predict the equivalent width of the strongest CN doublet of the 4215 Å CN 0–1 band. Using the line parameters and abundances described above, we get $W_\lambda = 1.6$ mÅ. From the catalog of Fraunhofer lines of Moore *et al.* (1966), the equivalent width of this doublet in the solar spectrum is $W_\lambda = 16$ mÅ, or

$$[W/\lambda] \simeq [X_{CN}] \simeq -1.0\,,$$

where $[X_{CN}]$ represents the shift of the abscissa of the curve of growth. Ball and Pagel (1967) give $[X_{CN}] = -2.1$ for [N/H] = [Fe/H] $\simeq -2.6$. Using our determination of [N/H] = [Fe/H] + 1.2, we then get $[X_{CN}] = -0.9$, which is consistent with our calculations. With the nitrogen overabundant even by this amount, the CN 0–1 band should still be invisible.

d) OH

The OH ($A\,^2\Sigma^+ - X\,^2\Pi_i$) ultraviolet band system contains some lines as far to the red as 3500 Å (see Dieke and Crosswhite 1962). There are no bandheads in this region, so a curve of growth was calculated for individual OH lines by varying the oxygen abundance input to the line analysis program. For the strongest line, it was found that

$$W = 0.7 \text{ mÅ} \quad \text{for} \quad [\text{O/H}] = [\text{Fe/H}]\,,$$
$$= 18.3 \text{ mÅ} \quad \text{for} \quad [\text{O/H}] = [\text{Fe/H}] + 1.5\,.$$

Conti *et al.* (1967) failed to detect the [O I] 6300 Å line on their plates of HD 122563 and gave an upper limit to the equivalent width of 12 mÅ. Using this equivalent width and Wolffram's (1972) model, it was found that [O/H] $\leq$ [Fe/H] + 0.9. In view of this result, and the small number of OH lines covered by the plates taken, the search for OH lines was dropped. It ought to be pointed out, however, that the lines in this spectral region are from the weak 0–1 band. The stronger 0–0 band ought to be easily seen if one can obtain spectra at 3100 Å.

e) $^{12}C/^{13}C$

An attempt was made to improve on the Cohen and Grasdalen (1968) upper limit ($^{12}C/^{13}C \geq 5$) using the ^{12}CH and ^{13}CH lines in the region of 4380–4400 Å. While

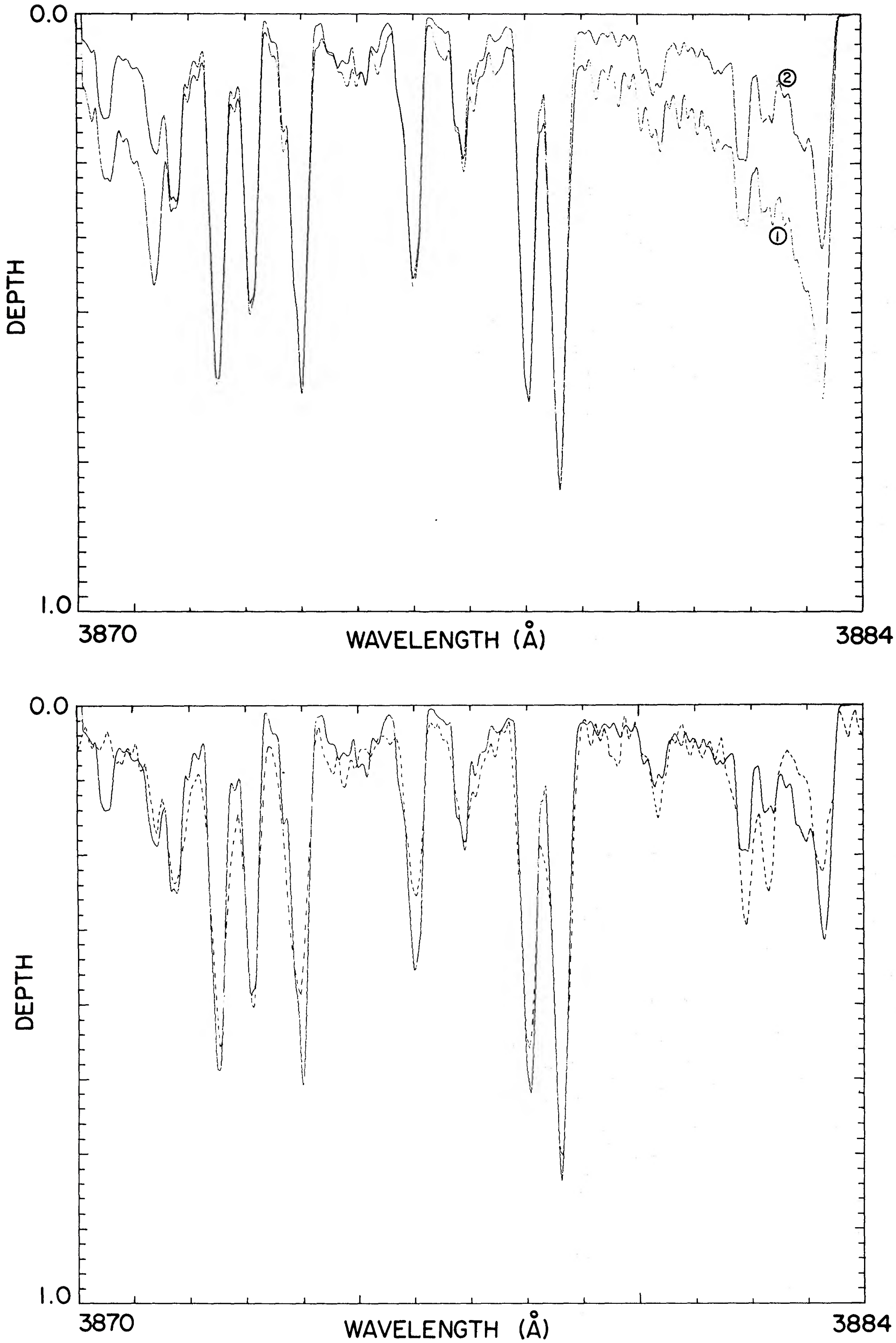

FIG. 4.—The CN spectrum. (*a*) (*top*) Synthetic spectra for (1) [C/H] = [Fe/H] − 0.4, [N/H] = [Fe/H] + 1.3, and D_{CN} = 7.85 eV, and (2) [C/H] = [Fe/H] − 0.4, [N/H] = [Fe/H] + 1.2, and D_{CN} = 7.55 eV; (*b*) (*bottom*) The solid line is the synthetic spectrum for [C/H] = [Fe/H] − 0.4, [N/H] = [Fe/H] + 1.2, and D_{CN} = 7.55 eV. The broken line is the observed spectrum.

the isotope shifts are high (around 0.5 Å) in this region, it turns out that the lines are simply too weak to be detected with the available plate material.

The logarithms of the carbon and nitrogen abundances relative to hydrogen cannot be specified better than ±0.4, mainly because of the uncertainties in the model atmosphere parameters for HD 122563. Pagel (1964) shows that in applying the differential curve-of-growth method to molecular lines,

$$[C/H] = [X_{CH,\chi=0}] - [P_H] + [P_e] - 2.73\Delta\theta - [\theta]\,,$$

where $[X_{CH,\chi=0}]$ is the curve-of-growth shift of the CH lines of the star in question relative to the Sun, and θ is the reciprocal temperature $5040/T$. There is a similar equation for nitrogen in dealing with the NH bands, so that we have

$$[C/N] = [X_{CH,\chi=0}] - [X_{NH,\chi=0}] - (D_{CH} - D_{NH})\Delta\theta\,.$$

Since $D_{CH} = 3.45$ eV and $D_{NH} = 3.21$ eV, the probable errors in $\Delta\theta(\pm 0.04)$ cannot affect the carbon to nitrogen ratio. The uncertainty, then, in [C/N] comes only from the uncertainties in fitting the observed and synthetic CH and NH spectra. The error in each fit is estimated to be ±0.1, so we have [C/N] = +1.6 ± 0.2. The helium content has been assumed here to be 10 percent of the total number density of atoms in the atmosphere. The error in an assumed helium fraction might be expected to cause additional errors to appear in the determination of abundances from molecular lines, but Schadee (1964) has shown that the helium content has no effect on abundances derived from lines of C_2, CN, CH, etc.

A final source of error involves our assumption that the radiative transfer can be adequately described with the LTE expressions. In order to test the effect on our answers of a more rigorous treatment of the problem, two cases were examined. In the first case, Rayleigh scattering was taken explicitly into account in computing the source functions, and it was assumed that the lines were all formed by pure scattering. The predicted line strengths were found to be 55 percent of the LTE ones for the NH lines, 60 percent for the CN lines, and 64 percent for the CH lines. In this case, carbon still would be underabundant by a factor of 2, while nitrogen would become overabundant by a factor of 30 relative to iron. In the second case, Rayleigh scattering again was taken into account for the source function computations, but it was assumed that the lines were formed by pure absorption. In this case predicted line strengths matched the LTE ones within 2 percent. The effect is not negligible, then, in the case where we assume that lines are formed by pure scattering, but even here our basic conclusions are not altered. Note also that there should be a similar effect in the Sun, and since we are in effect working differentially from the Sun, matching the solar molecular bands implies that our answers for HD 122563 cannot be far wrong.

V. CONCLUSIONS

This result for the nitrogen abundance is a rather unexpected one. Two other metal-poor stars have had a fairly detailed nitrogen abundance analysis performed. Harmer and Pagel (1970) studied two metal deficient stars, using individual rotational lines of the 3883 Å CN band. They found a marked underabundance, [N/Fe] = −0.74 ± 0.16, for the halo subgiant ν Indi, and a slight overabundance, [N/Fe] ≃ +0.5, for the halo subdwarf HD 25329. Bell (1970) has confirmed the nitrogen underabundance for ν Indi, using a model-atmosphere analysis. As Harmer and Pagel (1970) point out, other stars of low metal content have been analyzed for nitrogen content but the other studies have used the weak and badly blended 4215 Å CN band and therefore presumably are untrustworthy (i.e., see Koelbloed 1967). One can see that there simply is insufficient data to arrive at a definite conclusion about the nitrogen abundance in metal-poor stars. It is worth noting that the position of HD 122563 on the H-R diagram makes it possible for helium flashing to have occurred, and thus possible for deep mixing of the type proposed by Sackmann, Smith, and Despain (1972) to have occurred. The effect of the flash is to enhance the surface nitrogen abundance and to decrease the surface carbon abundance. Other stars are presently being analyzed by the author, using the CH and CN bands only. Also, an attempt will be made to obtain NH band data for as many of these stars as possible.

I wish to thank Dr. David L. Lambert for suggesting this project. Both he and Dr. W. David Arnett were helpful in discussing this work. Mr. Mark A. Powell performed much of the labor of tracing the plates. Thanks also goes to a helpful referee who made a particularly useful remark on one aspect of the computations. This project has been supported in part by grants from the Robert A. Welch Foundation of Houston, Texas and from the National Science Foundation (GP-32322X).

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