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THE OXYGEN ABUNDANCE IN THE METAL-DEFICIENT STAR HD 122563

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ABSTRACT

The forbidden neutral oxygen line at 6300.3 Å has been detected in the spectrum of the metal-deficient star HD 122563. The [O I] equivalent width, $W_\lambda = 6.0 \pm 1.0$ mÅ, and a model-atmosphere analysis provide an oxygen abundance $\log [N(\mathrm{O})/N(\mathrm{H})] = -5.38 \pm 0.15$ or a logarithmic overabundance of oxygen relative to the metals of [O/Fe] = +0.6. This relative overabundance of oxygen may be common to other metal-deficient stars. The probable role of convective mixing in altering the surface composition of evolved metal-deficient stars is pointed out.

Subject headings: abundances, stellar — convection — stars, individual — weak-lined stars

I. INTRODUCTION

The bright metal-deficient star HD 122563 has been studied extensively. Recently, Wolffram (1972) undertook a model-atmosphere calculation and derived an iron-abundance deficiency

$$\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right] = \log\left(\frac{\mathrm{Fe}}{\mathrm{H}}\right)_{122563} - \log\left(\frac{\mathrm{Fe}}{\mathrm{H}}\right)_{\odot} = -2.72 \pm 0.3 \,.$$

Sneden (1973) analyzed CH, CN, and NH electronic transitions in the blue and ultraviolet regions of the spectrum to obtain the C and N abundances. The result [C/Fe] = -0.4 ± 0.1 confirmed Wolffram's result obtained from a few CH lines. The nitrogen abundance was surprisingly high: [N/Fe] = $+1.2 \pm 0.1$. These results are displayed in table 1.

In view of these interesting relative-abundance differences for C and N, a determined effort was made to detect the previously unobserved forbidden oxygen line at 6300.3 Å. As Pagel (1969) has emphasized, the [O I] line should be detectable; the low solar equivalent width (W_λ = 4.1 mÅ, Mallia 1968) and the extreme metal deficiency are offset by the large column density afforded by a giant atmosphere. In fact, the [O I] line is predicted to have $W_\lambda \simeq 1$ mÅ even for [O/H] $\simeq -3.0$. These considerations led to this attempt to observe the line.

II. OBSERVATIONS

High-resolution photoelectric spectral scans of the [O I] 6300.3 Å line were obtained on four nights in 1973 April with the McDonald Observatory 107-inch (2.7-m) reflector and the Tull echelle coudé scanner. The scanner is described by Tull (1972). The entrance and exit slits of the scanner were set to correspond to a width of 0.1 Å. A scan of about 2 Å was made with a sampling interval of 0.025 Å. A counting rate of about 60 counts s^{-1} in each channel was recorded in good seeing using an RCA gallium arsenide photomultiplier. The combined sky and dark count rate was between 1 and 2 counts s^{-1}. (Inadvertently, the observations were acquired with the gratings in the less efficient of two possible configurations and a counting rate of 100 counts s^{-1} per channel is possible.) The sensitivity of the scanner shows a smooth variation across the length of the scan. A scan of a quartz-iodine lamp was made to determine this variation.

The sum of the individual scans is illustrated in figures 1 and 2. This represents 11 hours of integration. A total of about 20,000 counts was obtained in each channel. The statistical photon counting noise is about ±0.7 percent. This noise level is approached in the continuum regions of the scans. The plotted spectra have not been smoothed, although the 0.025 Å channel width provides an oversampling of the 0.1 Å slit width.

Figure 1 shows a preliminary reduction of the data after division by the quartz-iodine lamp scan. This procedure does not remove completely the sensitivity variation of the scanner. It is presumed that the illumination of the gratings by the star and the lamp are not identical. The estimated continuum level for the stellar scans is shown by the broken line in figure 1. In figure 2, the final reduction of the data for the [O I] and Sc II region for HD 122563 is shown with the data points normalized to this latter continuum.

TABLE 1

CARBON, NITROGEN, AND OXYGEN ABUNDANCES

Element	[N(el)/N(H)]	[N(el)/N(Fe)]
C................	−3.1 ± 0.4	−0.4 ± 0.4
N................	−1.5 ± 0.4	+1.2 ± 0.4
O................	−2.1 ± 0.4	+0.6 ± 0.4
Fe................	−2.7 ± 0.3	0.0

III. IDENTIFICATION AND MEASUREMENT OF THE [O I] LINE

The absorption feature is real; it was shown clearly on each of the four separate scans. The line is stellar in origin. No telluric (O_2 or H_2O) line is listed (Moore,

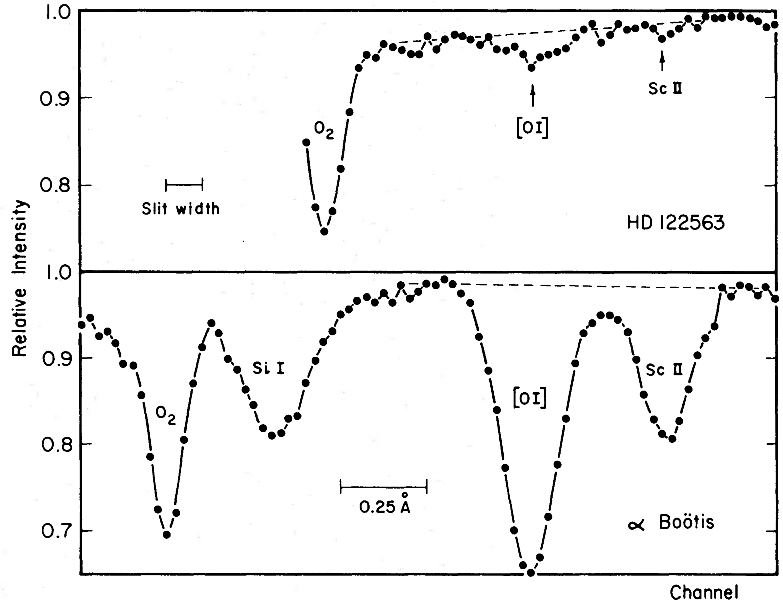

FIG. 1.—Scans of the 6300 Å region for HD 122563 and Arcturus. The observed scans have been divided by the lamp scan (see text) to correct for the variation of instrumental response across the scan. This correction does not completely remove the variation and the stellar continuum level is shown by the broken line. The stellar scans are displayed so that stellar features are aligned. The displacement of the telluric O_2 feature gives the relative radial velocity between HD 122563 and Arcturus.

Minnaert, and Houtgast 1966) to fall at the Doppler shifted position of the [O I] line and none is observed in either the sky or Arcturus scans (fig. 1).

When a short spectral region is scanned, the wavelength scale must be determined with care. A reference wavelength is provided by the telluric O_2 ($+H_2O$) line at 6299.228 Å which was included in all scans. The wavelength scale was derived from scans of the Arcturus spectrum in which the O_2, [O I], Sc II lines and the line at 6299.60 Å were readily identified. The latter line is unidentified by Moore *et al.* but Lambert and Warner (1968) attributed it to Si I. The radial velocities (rv) are known: $rv = -5.25 \pm 0.02$ km s^{-1} for Arcturus (Petrie and Fletcher 1967) and $rv = -25.0 \pm 0.5$ km s^{-1} for HD 122563 from references cited by Abt and Biggs (1972) and Evans (1973). The radial velocities for the time of observation were computed with the Arcturus scan serving as a check on the calculations. The predicted position of the [O I] line in HD 122563 is shown in figures 1 and 2. This prediction is within one channel of the observed center of the absorption line. This is pleasing agreement.

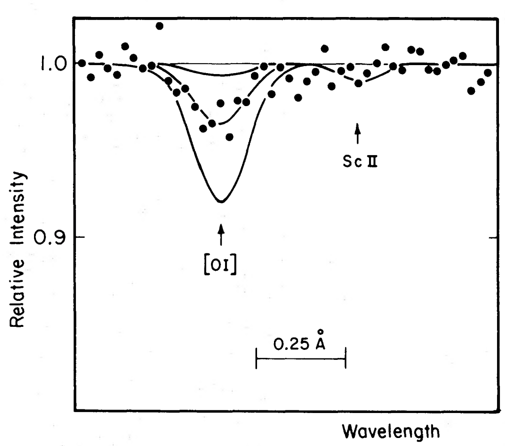

FIG. 2.—Observed and synthetic spectra of the [O I] and Sc II lines in HD 122563. The observed scan is replotted from fig. 1 and the data points have been normalized to the continuum level (*broken line*) of fig. 1. Synthetic spectra are shown for abundances [O/Fe] = 0.0, +0.6, +1.0.

The equivalent width for the [O I] line is estimated to be $W_\lambda = 6.0 \pm 1.0$ mÅ. The Sc II line at 6300.678 Å is tentatively identified and $W_\lambda \lesssim 1.5$ mÅ is estimated.

IV. THE OXYGEN ABUNDANCE

The interesting result of the analysis is that oxygen is not as deficient as the metals. This is demonstrated by calculations performed using the model atmosphere given by Wolffram (1972) for HD 122563 and the Harvard-Smithsonian Reference Solar Atmosphere (Gingerich *et al.* 1971). The solar equivalent width, $W_\lambda = 4.1$ mÅ, corresponds to a product $\log (gf\epsilon)_\odot = -12.91$ where $\epsilon = N(\mathrm{O})/N(\mathrm{H})$. The stellar equivalent width, $W_\lambda = 6.0$ mÅ, gives

$$\log (gf\epsilon)_{122563} = -15.05$$

and, hence, [O/H] = -2.14 ± 0.15. This provides [O/Fe] = +0.6 when the abundance [Fe/H] = -2.72 ± 0.3 (Wolffram 1972) is adopted. Similar calculations for the Sc II line give a predicted $W_\lambda = 1.0$ mÅ from a fit to the solar line which is consistent with the present scan.

In figure 2, the predicted [O I] profiles are shown fitted to observations. These synthetic spectra were generated for the three abundances [O/Fe] = 0.0, +0.6, and +1.0. The Sc II line was included with an oscillator strength calculated from the solar equivalent width. The telluric O_2 line has a very narrow intrinsic profile, and thus the observed profile is regarded as a satisfactory representation of the instrumental profile of the scanner. The synthetic spectra have been smoothed using the O_2 profile.

A method of differential abundance analysis can be used to confirm the oxygen overabundance. Neutral oxygen and singly ionized scandium behave similarly throughout the atmospheres of the Sun and HD 122563. The excitation potentials are reasonably similar: $\chi = 0.0$ eV for [O I] and $\chi = 1.51$ eV for the Sc II line. Then, in the notation of Pagel (1964), the stellar abundance ratio becomes

$$[\mathrm{O/Sc}] = [X_{\mathrm{O}}/X_{\mathrm{Sc}}] + \Delta\theta_{\mathrm{exc}}(\chi_{\mathrm{O}} - \chi_{\mathrm{Sc}})$$

$$= [W_\lambda(\mathrm{O})/W_\lambda(\mathrm{Sc\,II})] - 1.51\Delta\theta_{\mathrm{exc}}\,.$$

The difference $\Delta\theta_{\mathrm{exc}}$ in the reciprocal excitation temperatures for ionized lines is $\Delta\theta_{\mathrm{exc}} = 0.19 \pm 0.02$ (Pagel 1965). On substitution of the equivalent widths given above together with $W_\lambda = 5.0$ mÅ for the solar Sc II line (this was measured off a figure given by Mallia 1968), the ratio obtained is

$$[\mathrm{O/Sc}] \geq 0.40\,,$$

where the stellar equivalent width for the Sc II line is taken as an upper limit. A small correction ($\sim$1 percent) should also be added to this ratio to allow for the small amount of oxygen which is associated as CO.

An attempt was made to derive the O abundance directly from the differential analysis. This gave a result which was not in agreement with either the above upper limit or the result of the model-atmosphere analysis. The reason appears to be that in this approach the electron pressure ratio [*Pe*] is used and that this shows a significant variation with line type and strength: a comparison of the model atmospheres for the star and Sun shows this. Pagel derived [*Pe*] from moderately strong lines and, hence, his [*Pe*] is not representative of the regions of formation for the weak [O I] and Sc II lines. This factor cancels out when the [O I] and Sc II lines are intercompared.

The present result is reasonably consistent with an upper limit reported previously. Conti *et al.* (1967) gave $W_\lambda < 12$ mÅ for the [O I] line and calculated that [O/H] ≤ -1.8 to -2.0 depending on the amount of CO association. This analysis gives [O/H] = -2.14.

V. DISCUSSION

The abundances (table 1) of the light elements, C, N, O in HD 122563 present an interesting problem: the abundances relative to the metals show carbon underabundant by a factor of 3, nitrogen overabundant by a factor of 15, and oxygen overabundant by a factor of 4.

Information on the oxygen abundance in other metal-deficient stars is meager. Conti *et al.* (1967) did note that oxygen was probably overabundant ([O/Fe] > 0) for the three weak-lined stars in their sample. Horizontal-branch A stars have been analyzed by Kodaira and Tanaka (1972). Their upper limit for oxygen would not exclude a slight overabundance relative to the metals. The presence of a planetary nebula in the globular cluster M15 provides another point of comparison. Peimbert (1972) in an analysis, which supersedes that by O'Dell, Peimbert, and Kinman (1964), found that the oxygen deficiency was [O/H] $\simeq -1.0$ while the stars have a metal deficiency [Fe/H] $\simeq -2.0$ and, hence, [O/Fe] + 1.0. Then, there is evidence, which with the new result for HD 122563, would suggest that oxygen deficiencies in metal-poor stars are not so extreme as the metal deficiencies.

The present abundances may not be representative of the initial stellar composition. As a star evolves to the red-giant tip, convective mixing (Iben 1964) is predicted to contaminate the envelope with nuclear processed material from the interior. A recent high-dispersion spectroscopic analysis of two K giants (Day, Lambert, and Sneden 1973) has shown that these atmospheres contain a high abundance of ^{13}C which is in qualitative agreement with the theoretical prediction. Although calculations have not been reported for metal-deficient stars, it would appear likely that these stars (e.g., HD 122563) must also undergo this mixing. As a result of mixing, the surface N/C ratio is enhanced and the ^{12}C/^{13}C ratio is reduced; the interior has burnt C to N and the ^{12}C/^{13}C ratio is there at the low equilibrium value. The observed N/C ratio may reflect in part the consequence of mixing. An attempt is being made to identify or to establish good upper limits for ^{13}CH lines to improve upon the limit (^{12}C/^{13}C > 5) set by Cohen and Grasdalen (1968); a demonstration that the ^{13}C abundance was high would constitute fairly conclusive evidence that mixing had occurred. The oxygen abundance is likely to be only slightly reduced by mixing below the initial value, and, hence, the relative overabundance of oxygen would appear to be representative of the initial composition of the star. Mixing with simultaneous nuclear processing can also occur during the helium-flash stage. The probable occurrence of mixing and alterations to the surface abundances for light elements introduces an extra dimension to discussions of abundances analyses of evolved metal-deficient stars and the chemical evolution of the Galaxy.

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