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THIRTEEN-COLOR PHOTOMETRY OF SUBDWARF STARS. IV. HD 25329 AND HD 122563

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RESUMEN

Los excesos ultravioletas anómalos de HD 25329 y HD 122563 se explican debido a sus abundancias de nitrógeno (absorciones por las bandas 3360A (0-0) y 3370A (1-1) de NH) y por dispersión de Rayleigh. Se demuestra que la fotometría de ocho colores se puede usar para la identificación de estrellas enanas (pobres en metales) de *45-63* $\gtrsim$ + 1.0, con sobreabundancia de nitrógeno. La curva de diferencia de colores de la gigante extremadamente pobre en metales HD 122563 muestra muy claramente la creciente importancia de la dispersión de Rayleigh con respecto al proceso H^- como fuente de opacidad en el continuo.

ABSTRACT

The unusual ultraviolet excesses of HD 25329 and HD 122563 are explained by their nitrogen abundances (absorption by the 3360A (0-0) and 3370A (1-1) bands of NH) and by Rayleigh scattering. For *45-63* $\gtrsim$ + 1.0 eight-color photometry can be used to identify (metal poor) dwarf stars with nitrogen overabundances. The difference curve of the extremely metal-poor giant HD 122563 shows very distinctly the increased importance of Rayleigh scattering with respect to the H^- processes as a source of continuum opacity.

Key words: PHOTOMETRY – STARS-ABUNDANCES – STARS-SUBDWARFS.

I. INTRODUCTION

In Paper I (Schuster 1979*a*) we used a differencing technique to study the compositon and gravity sensitivities of 13-color photometry for F, G, and early-K stars. The ultraviolet excesses of most stars were easily understood in terms of blanketing curves, which change little with temperature, or in terms of gravity-difference curves. However, a few stars such as HD 25329 and HD 122563 (Schuster 1976*a*) do not fit well into this simple pattern. Both these stars do show excesses in filters *33*, *35*, *37* and *40* when compared to stars with approximately Hyades-like compositions. However, unlike the subdwarfs of Paper I, the *33* excesses of both stars are considerably less than their *35* and *37* excesses, leading to *33-35* deficiencies. This distinction between "excess" and "deficiency" should be kept in mind. In this paper we extend the versatility of the differencing technique by explaining the ultraviolet observations of these two stars.

II. OBSERVATIONS

In Table 1 we give the 13-color observations of HD 25329 and HD 122563 made at the Observatorio Astronómico Nacional in Baja California; also given are the standard deviations of the mean for each color. The observations were taken and reduced in the same manner as described previously (Schuster 1976*a*, 1979*a*). The photometry of HD 122563 (BS 5270) and the 6RC observations of HD 25329 (BD + 34°796) have been published previously (Schuster 1976*b* and 1979*a*, respectively). Eight new 8C observations of HD 25329 have been averaged with the four original ones; the older 8C observations were given only half weight since the newer observations were taken using improved observing techniques.

TABLE 1

THIRTEEN COLOR PHOTOMETRY OF HD 25329 AND HD 122563

	HD 25329		HD122563	
Filter	Color	σ ($x10^{-13}$)	Color	σ ($x10^{-13}$)
52	8.735	7.0	6.392	26.0
33-52	1.083	13.0	1.292	4.0
35-52	0.679	6.0	0.916	5.0
37-52	0.978	5.0	0.880	8.0
40-52	1.027	6.0	1.052	4.0
45-52	0.373	4.0	0.510	3.0
52-58	0.465	4.0	0.430	13.0
52-63	0.767	4.0	0.760	15.0
NB	12(10)	....	3	....
58	8.324	10.0	6.011	16.0
58-72	0.588	9.0	0.656	10.0
58-80	0.805	8.0	0.901	12.0
58-86	0.894	16.0	1.023	9.0
58-99	1.023	13.0	1.183	8.0
58-110	1.191	5.0	1.344	13.0
NR	4	....	5	....

III. PHYSICAL PARAMETERS AND DIFFERENCE CURVES

In Table 2 we give physical atmospheric parameters for the two stars compiled from a number of sources. In addition to the usual composition parameter, [Fe/H], we have listed [N/Fe] since the nitrogen abundances will prove important in interpreting the *33-35* colors. The [Fe/H], temperature, and surface gravity of HD 25329 place it in the category of cool subdwarf, very similar in these three parameters to the K-type subdwarfs BD-15° 4041 and – 15° 4042 (HD 134439/40), (Schuster 1979*b*, 1976*a*, and references therein). However, HD 25329 and HD 122563 both belong to a very small group of metal-poor stars which have an overabundance of nitrogen with respect to the other metals (Sneden 1974). In this respect HD 25329 is different from BD – 15° 4041/2. HD 122563 was originally classed as a G0 subdwarf (Roman 1955; Hoffleit 1964), but more detailed studies soon showed that it is a metal-poor red giant similar to those in globular clusters (Wallerstein *et al.* 1963). The gravity and temperature of HD 122563 match it approximately with a bright giant of spectral class G5-K0 (Allen 1973).

In Figure 1 we give difference curves for HD 25329, BD –15° 4041/2, HD 122563, and various field giants, and in Table 3 we list the characteristics of these curves. Unfortunately the theoretical blanketing corrections of Kurucz (1975) which we applied to *45-63* to construct the blanketing curves of Paper I extend only to T_e = 5 500°, and so cannot be used directly for these cool stars. At 5 500° the more metal-poor subdwarfs, ([Fe/H]< – 1.0) require a *45-63* blanketing correction of approximately + 0.02 when compared to the Hyades mean colors at constant T_e. According to the arguments of Paper I we have extended this correction to the temperatures of HD 25329 and BD –15° 4041/2.

For metal-poor giants ([Fe/H] = – 1.0 to – 2.0) the theoretical colors at T_e = 5 500° and log g = 2.0 give *45-63* blanketing corrections of + 0.05-0.07, but other factors, such as Rayleigh scattering, could cause these corrections to be grossly in error for the temperature, gravity and extreme composition of HD 122563. For this reason, we have constructed difference curves for HD 122563 over a range of *45-63* values, and also over a range of luminosity classes to check whether the shape of the ultraviolet excesses are caused in part by gravity differences. The curves for HD 122563 were constructed by comparing to other field stars as listed in Table 3. The heavy symbols of Figure 1 give difference curves constructed from Stebbins and Kron six-color photometry (Sears and Whitford 1969), and the lowest four curves compare giants with approximately equal values of *45-63* but differing [Fe/H] values according to Morel *et al.* (1976).

In Figure 1 the difference curves of HD 25329 and HD 122563 turn down sharply at filter 33 unlike any of the blanketing curves of Paper I. We cannot use the gravity-difference curves of Paper I to explain HD 25329 since a turn-down of filter *35* is not observed; also there is no reason to suspect that the gravity of HD 25329 is not approximately main sequence. The main physical difference between HD 25329 and BD – 15° 4041/2 is the over-abundance of nitrogen in the former. We believe that the 3360Å (0-0) and 3370Å (1-1) bands of NH which are prominent in stars of solar temperature and cooler, provide the necessary blanketing to explain the *33* color of HD 25329. In Figure 2 we reproduce a portion of the solar spectrum from Minnaert *et al.* (1940). The broad dip at 3360Å which is largely due to NH (Butler *et al.* 1975; Sneden 1973) is centered on the maximum transmission of filter *33* (Johnson and Mitchell 1975). Moore *et al.* (1966) identified 265 lines of NH in the solar spectrum of which 264 lie within the 10% transmission limits of filter *33* (3275-3475Å) (Johnson and Mitchell 1975).

Gravity differences also cannot be used to explain

TABLE 2

ATMOSPHERIC PARAMETERS OF HD 25329 AND HD 122563

[Fe/H]	T_e	log g	[N/Fe]	References
		HD 25329		
–2.30	4200 (ion)	....	....	Heiser 1960
–1.32	4710	....	+ 0.50	Pagel and Powell 1966
....	4800	4.30	....	Schuster 1976*a*
....	4470:	....	....	Strom and Strom 1967
....	5160	....	....	Travis and Matsushima 1973
....	4670	....	....	Cayrel 1968
....	....	....	+ 0.55	Pagel 1973
....	....	4.60	+ 0.80	Harmer and Pagel 1973
....	....	....	+ 0.50:	Harmer and Pagel 1970
....	4570	....	....	Jones 1966
–1.34	4890	3.84 (spec.)	....	Hearnshaw 1976
....	4890	4.77 (trig.)	....	Hearnshaw 1976
–1.49	4710	3.46 (s)/4.79(t)	....	Hearnshaw 1976; Pagel and Powell 1966
–0.90	....	....	....	Taylor 1970
–1.50	4730	4.30	+ 0.60	Average Value
		HD 122563		
–2.65	4420	1.20	....	Pagel 1965
–2.70	4240	....	....	Wallerstein *et al.* 1963; Wallerstein and Helfer 1966
–2.75	4600	1.20	....	Wolffram 1972
–2.75	4600	1.20	+ 1.20	Sneden 1973
–2.60	4200	....	≤ + 0.70	Ball and Pagel 1967
....	....	....	+ 0.35	Pagel 1973
....	....	....	≤ + 0.40	Harmer and Pagel 1973
....	....	....	+ 1.20	Sneden 1974
–2.70	4410	1.20	+ 0.80	Average Value

TABLE 3

DIFFERENCE CURVES OF FIGURE 1

Stars	Comparison	Photometry*	Symbol in Figure 1	(*45-63*) Blanketing Correction, ([Fe/H])†
HD 25329	Hyades M.S.	13C	Squares	+ 0.02
BD –15°4041	Hyades M.S.	13C	Circles	+ 0.02
BD –15°4042	Hyades M.S.	13C	Triangles	+ 0.02
HD 25329	Hyades H25 and H91	6C	Heavy crosses	Constant (R-I)
HD 122563	BS 3, BS 188, BS 351 (G8-KIIII)	13C	Circles	Constant (*45-63*)
HD 122563	BS 6536, BS 7063 (G2,G5II)	13C	Triangles	+ 0.027
HD 122563	BS 649 (G8II)	13C	Diamonds	– 0.146
HD 122563	BS 6536 (G2II)	13C	Crosses	– 0.062
HD 122563	BS 7747 (G3Ib)	13C	Squares	+ 0.063
HD 122563	BS 7747 (G3Ib)	6C	Heavy Pluses	(R-I)–0.07
BS 163 (G8IIIp)	BS 6148 (G8III)	13C	Circles	+ 0.022, (–0.75, + 0.41)
BS 4608 (G8III)	BS 1346 (K0III)	13C	Squares	+ 0.006, (–0.60, + 0.09)
BS 2990 (K0III)	BS 3994 (K0III)	13C	Triangles	+ 0.006, (–0.51, + 0.12)
BS 4518 (K0III)	BS 7064 (K3III)	13C	Diamonds	+ 0.002, (–0.65, 0.00)

* 13-color or Stebbins and Kron 6-Color.
† [Fe/H] of star and comparison, respectively.

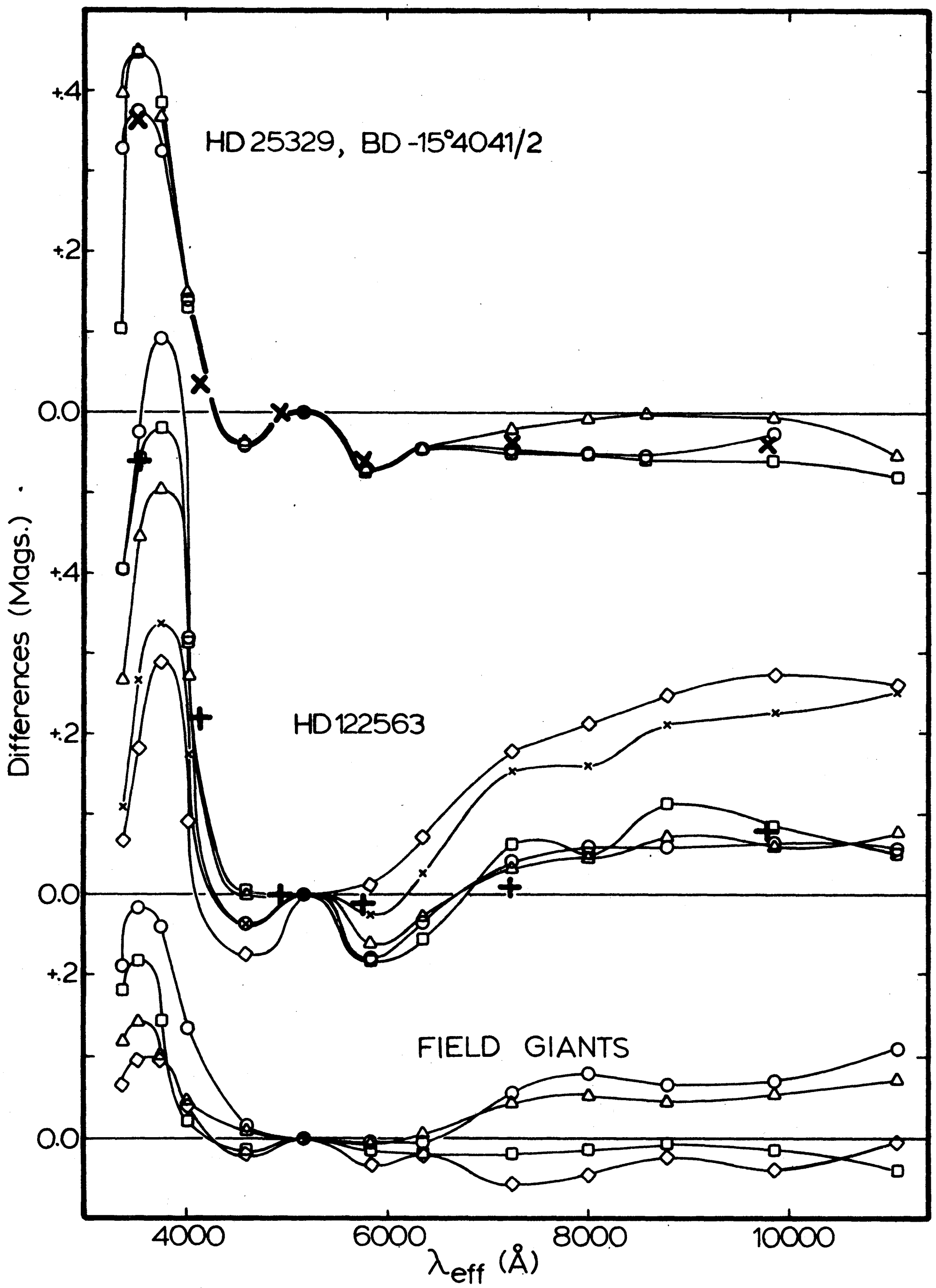

Fig. 1. Difference curves for HD 25329, BD-15°4041/2, HD 122563, and various field giants. The details of the comparisons are given in Table 3.

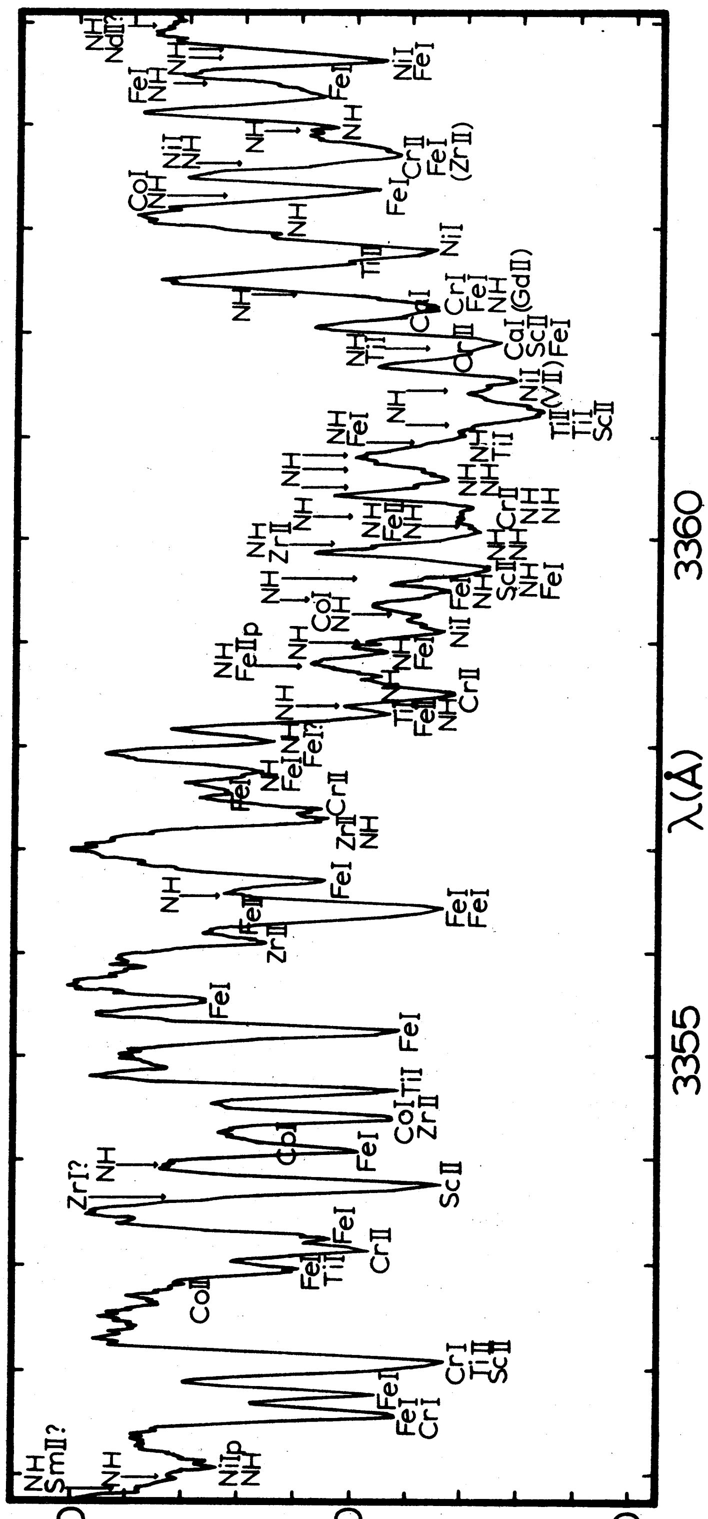

Fig. 2. That part of the solar spectrum (Minnaert *et al.* 1940) near the maximum transmission of the *33* filter, 3360 Å (Johnson and Mitchell 1975). The line identifications come from Moore *et al.* (1966).

the curves of HD 122563. We have used giants, bright giants, and a supergiant as comparison stars, and yet see little change in the shape of the ultraviolet excess; a sharp turn-down in filters *35* and especially *33* are seen in all cases. The spectra of Sneden (1973) show that NH absorption is also present in HD 122563, but this is only part of the explanation. Wallerstein *et al.* (1963), Pagel (1963), Wolffram (1972), and Böhm-Vitense (1973) show that for the low gravity and extreme metal deficiency of HD 122563 the continuous opacity source is different from that in usual metal-rich giants; Rayleigh scattering by neutral hydrogen makes a not negligible contribution when compared to the decreased importance of the H^- processes. We believe that the difference curves of HD 122563 turn-down sharply in the ultraviolet due to the λ^{-4} dependence of Rayleigh scattering, and that the excess for $\lambda > 6000$Å is produced by the low relative opacity of Rayleigh scattering at these wavelengths compared to H^-. The overall ultraviolet excess (filters *33, 35, 37* and *40*) is caused by the usual blanketing effects discussed in Paper I. A simple model applying three continuum absorbers to a normal giant star, one varying with wavelength blanketing curves of Paper I, one varying as λ^{-4}, and one varying negatively as the H^- bound-free and free-free processes (Allen 1973), produces remarkably well the difference curves of HD 122563 where only the relative contributions are adjusted for best fit.

IV. COLOR-COLOR DIAGRAM: *33-35 vs. 45-63*

In Figure 3 we plot (*33-35, 45-63*) diagrams using the data of Johnson and Mitchell (1975) and of Schuster (1976*b*, 1979*a*, 1980). In Figure 3*a* the fiducial line for giants has been defined by stars of luminosity classes III, II-III, and II. The Hyades mean colors give the dwarf fiducial line for (*45-63*)$< +1.0$, and for (*45-63*)$> +1.0$ a compromise between the mean Hyades colors and the colors of three field dwarfs, BS 753, BS 1084, and BS 8832, which are 13-color standards, has been made; at K2 and K4 the Hyades mean colors are not well defined (Schuster 1979*a*). In Figure 3*b* we plot the subdwarfs from Paper I as well as the two stars under study and a few metal-poor giants (Schuster 1980). HD 25329, HD 122563, and the two extremely metal-poor giants, HD 221170 and HD 165195 (Morel *et al.* 1976), are the only stars to show large *33-35* deficiencies. Unfortunately not many extremely metal-poor giants are known for making a good comparison with HD 122563. BD $+41°3735$ and BD-9°5491 from Paper I are metal-poor giants, do not exhibit deficiencies in Figure 3*b*, but are also less-metal-deficient and much bluer than HD 122563. The giants HD 2665 and HD 201626 are more than a factor of ten less metal-deficient than HD 122563 (Morel *et al.* 1976) and have larger gravities (from the compilation of Harmer and Pagel 1973), and HD 201626 is a CH Star (Wallerstein and Greenstein 1964) with overabundances of carbon and several other heavy elements with respect to the iron abundance.

In Figures 4 and 5 we show the dependence of δ(*33-35*) upon the composition parameters [Fe/H], δ(*33-45*), and [N/Fe] for stars observed by Johnson and Mitchell (1975) and Schuster (1979*a*, 1980) The [Fe/H] values come from Morel *et al.* (1976) or from Schuster (1979*b*), and the N/Fe values from many sources (Harmer and Pagel 1970, 1973; Bell 1970; Tomkin 1972; Tomkin and Bell 1973; Pagel 1963,1973; Pagel and Powell 1966; Sneden 1973,1974; Clegg 1977; van Paradijs and Kester 1976; Lambert and Ries 1977; Greene 1969; Mackle *et al.* 1975; Morel *et al.* 1976). The ultraviolet parameters δ(*33-35*) and δ(35-45) are defined as the difference between a star's observed value and a mean curve at constant *45-63*; the mean curves are defined by Hyades stars or field stars as in Figure 3. We use the spectroscopic (or photometric) [Fe/H] values and the blanketing parameter δ(35-45) as measures of the overall metallicity. We saw in Paper I that for G giants *35-45* is a good metallicity index and is insensitive to surface gravity.

In Figure 4*a* we see that for *dwarfs* (triangles and crosses), δ(*33-35*) definitely does not depend upon [Fe/H] and that HD 25329 stands distinctly apart from other subdwarfs with similar [Fe/H]'s. For *giants* (circles), δ(*33-35*) perhaps does depend upon the overall metallicity, but there is limited data. In Figure 4*b* we plot δ(*33-35*) *versus* δ(*35-45*) for only giants and see a fairly well defined dependence of δ(*33-35*) upon the overall blanketing. However, again we note that few giants with δ(*35-45*)$> +0.4$ have been observed and that there is some scatter, notably HD 2665.

In Figure 5 we see no evidence that the index δ(*33-35*) can be calibrated to give [N/Fe] values. However, for the dwarf stars of Figure 5*a* only three beside HD 25329 have [N/Fe]> 0: HD 10476 (*45-63* $= +1.042$ and [N/Fe] $= +0.1$), HD 157214 ($+0.842$ and $+0.15$) and HD 20630 ($+0.865$ and $+0.25$). Two of these are considerably bluer (hotter) than HD 25329 with *45-63* $= +1.140$. Also, except for HD 103095 with *45-63* $= +1.003$, [N/Fe] $= -0.7$, and [Fe/H] $= -1.25$ the dwarfs of Figure 5*a* are all metal-rich compared to HD 25329.

Most of the giants in Figure 5*b* have [N/Fe]> 0.0, and several are as red or redder than HD 122563. However, for only nine giants (including HD 122563)

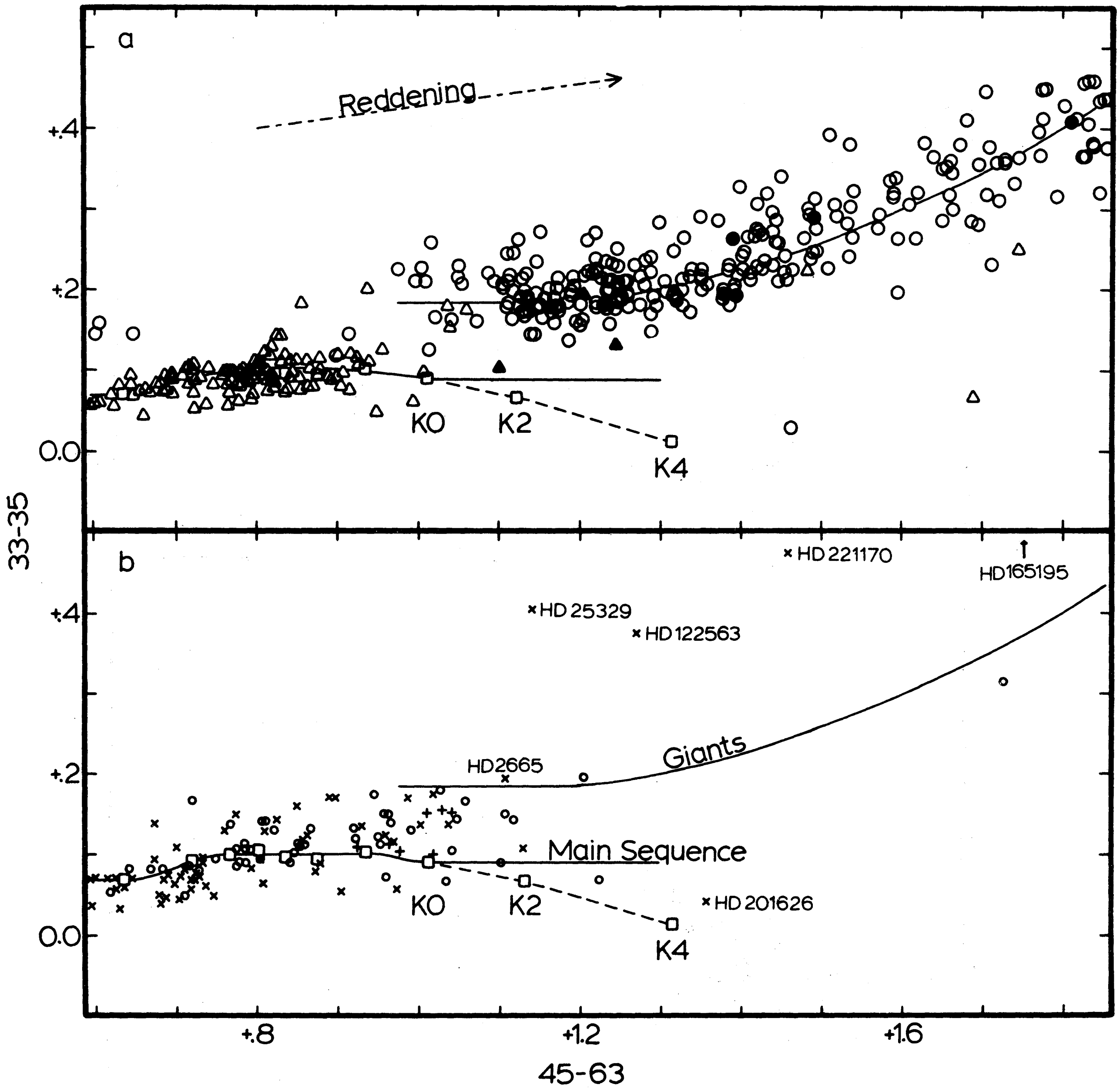

Fig. 3. The *33-35* versus *45-63* diagram. (*a*) Circles are for field giants (luminosity classes III, II-III, and II), triangles for field dwarfs (V and IV-V), and squares for Hyades mean colors. Filled circles and triangles indicate 13C standards. (*b*) Circles are for stars from Paper I with [Fe/H]> −1.0 (Schuster 1979*a*, 1979*b*) X's for [Fe/H]< −1.0 including four additional metal-poor field giants (Schuster 1980), pluses for the reddened stars of Paper I, and squares for Hyades mean colors. The fiducial lines are those defined in (*a*).

do we have directly determined [N/Fe] values. For the rest we have combined [N/H] values from the literature (see references above) with [Fe/H] values from Morel *et al.* (1976). These [N/Fe] values are less certain, and their circles in Figure 5*b* are marked with colons. For the giants we can see *no* correlation between $\delta(33\text{-}35)$ and [N/Fe] and also no correlation between the [N/Fe] values and the scatter of Figure 4*b*.

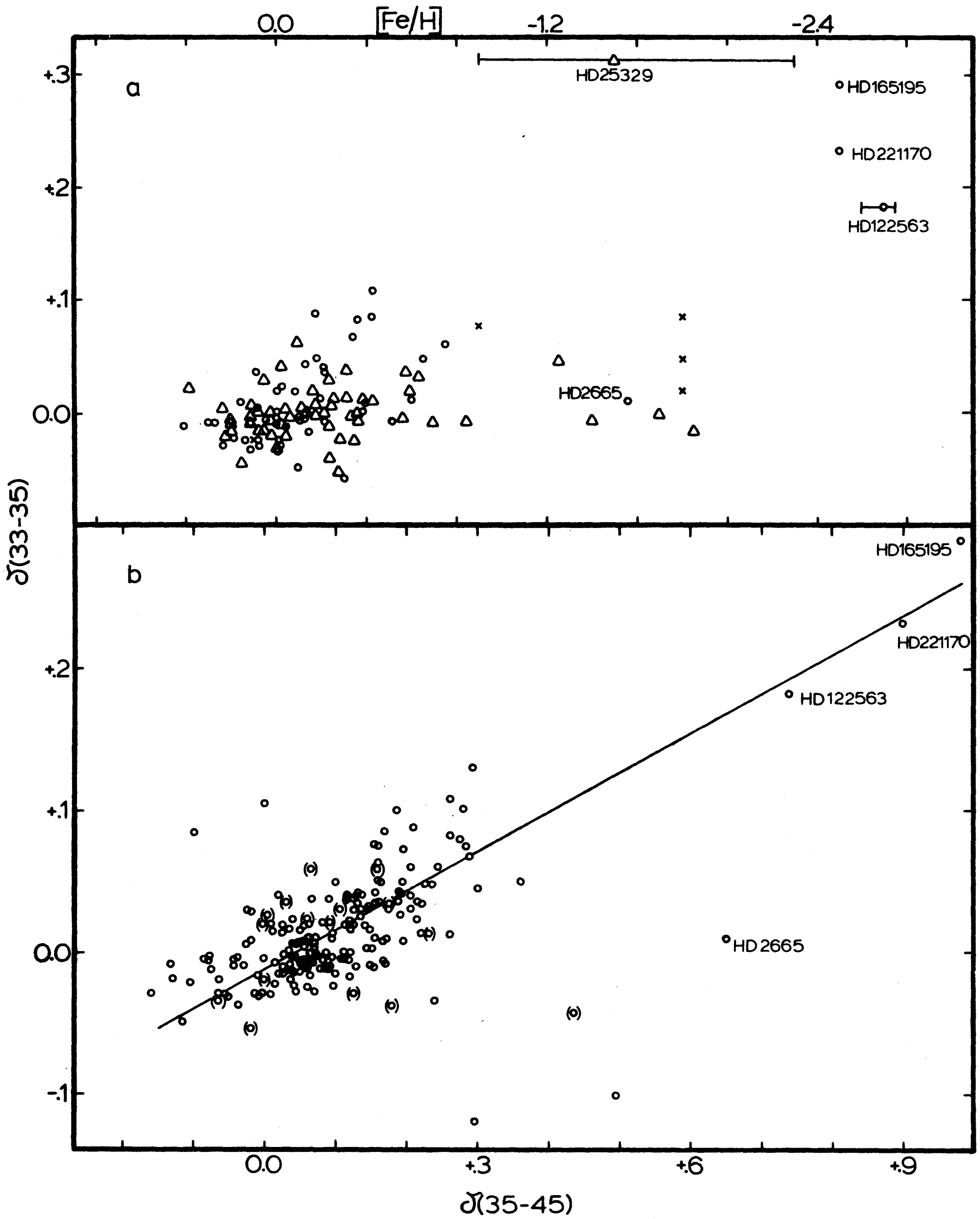

Fig. 4. (*a*) δ (*33-35*) versus [Fe/H]. Triangles represent field dwarfs with spectroscopic abundances (Morel *et al.* 1976) and + 0.7 < *45-63*< + 1.4, X's field dwarfs with photometric abundances (Schuster 1980) and *45-63*> + 1.0, and circles field giants with spectroscopic abundances and + 1.0<*45-63*< + 1.75. The bars for HD 25329 and HD 122563 show the range of published compositions from Table 2. (*b*) δ (*33-35*) versus δ (*35-45*) for giants (luminosity class III only) with + 1.1<*45-63*< + 1.75. Parentheses indicate that only a single 8C observation was made.

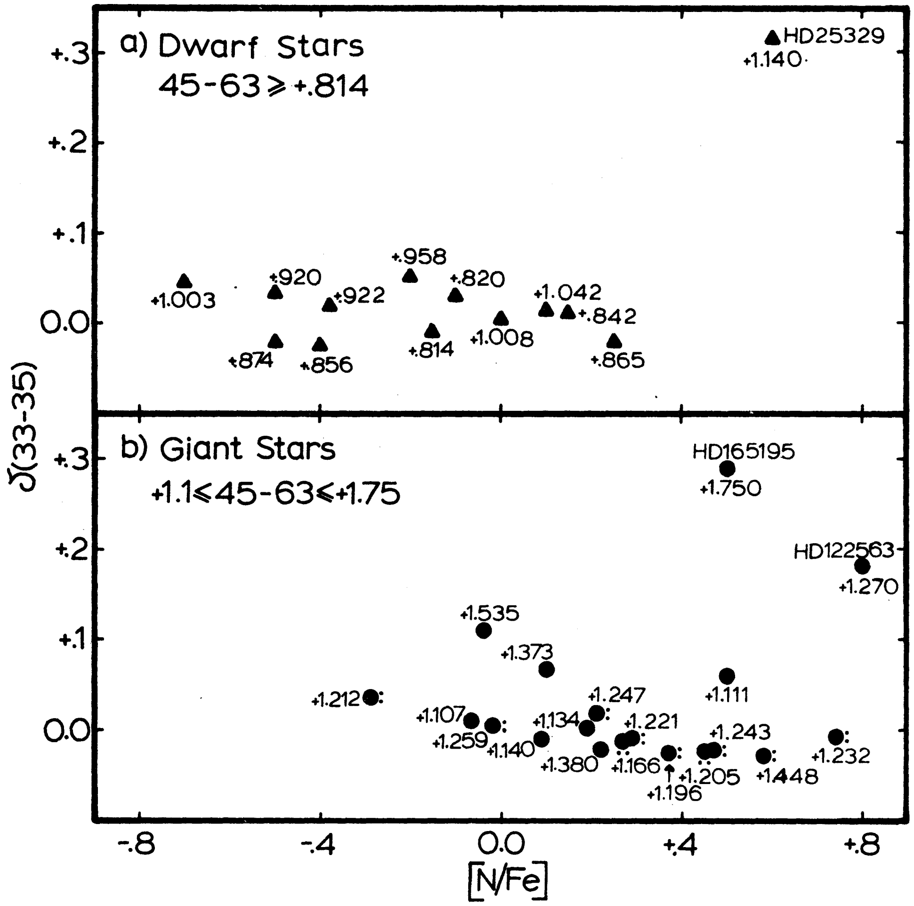

Fig. 5. δ (*33-35*) versus [N/Fe]. (*a*) Dwarf stars with *45-63*> + 0.814. The points are labeled with the stars' *45-63* values. (*b*) Giant stars with + 1.1<*45-63*< + 1.75. Colons indicate less certain [N/Fe] values, where [N/H] comes from one source (see text) and [Fe/H] from another (Morel *et al.* 1976).

V. CONCLUSIONS

For HD 25329 we believe that the coincidence of filter *33* with the NH bands, the unusual blanketing of *33* with respect to *35* and *37*, and the spectroscopically determined overabundances of nitrogen with respect to iron combine to corroborate, qualitatively at least, both our interpretation of the difference curves and the [N/Fe] values. The results also show that for dwarf stars *33-35* is independent of the overall metallicity as measured by [Fe/H] and suggest that, if sufficient calibration data were available, we could calibrate δ(*33-35*) to give [N/Fe] values for dwarfs with *45-63* $\gtrsim$ + 1.0, at least for metal-poor dwarfs. Without a calibration we can still use 8C photometry for this *45-63* range to identify (metal-poor) dwarfs with nitrogen overabundances.

For HD 122563 and the giant stars the *33-35* deficiency correlates well with the overall metallicity as measured by [Fe/H] or δ(*35-45*) and not with the nitrogen abundance. So, although we know that the *33* measure for HD 122563 does contain absorptions by the NH bands (Sneden 1973,1974) we conclude that the main effect in the *33-35* deficiency is produced by Rayleigh scattering. The extreme metal deficiencies of HD 122563, HD 165195, and HD 221170 produce extended, relatively transparent atmospheres in which Rayleigh scattering competes with the usual H^- processes. Although HD 122563 is cooler than HD 25329, we see no evidence that δ(*33-35*) can be used to give [N/Fe] values for giants. The smaller effect of the NH bands in the *33* measure of HD 122563 is due to the importance of Rayleigh scattering as a continuum opacity source for the wavelengths 3275-3475Å combined with HD 122563's much lower gravity and its greater nitrogen deficiency with respect to hydrogen ([N/H] = −1.9 for HD 122563 and [N/H] = −0.9 for HD 25329).

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