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Silicon Abundances in Population I Giants

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Abstract

Silicon to carbon abundance ratios for population I giants were determined from emission lines originating in the transition layers between stellar chromospheres and coronae. For effective temperatures larger than 6200 K we find a group of stars with increased silicon to carbon but normal nitrogen to carbon abundance ratios. These stars are presumably descendents from Ap stars with increased surface silicon to carbon abundance ratios. For G stars this anomaly disappears as is to be expected due to the increased depth of the convection zone and therefore deeper mixing which dilutes the surface overabundances.

The disappearance of the abundance anamolies proves that the anomalous abundances observed for the F giants are indeed only a surface phenomenon. It also proves that the same holds for their progenitors, the Ap and Am stars, as has been generally believed.

Unexplained is the increased silicon to carbon abundance ratio observed for several stars cooler than 5100 K. RS CVn and related stars do not show this increased abundance ratio.

There are also some giants which appear to be enriched in carbon, perhaps due to earlier mass transfer from an evolved companion or perhaps due to a helium flash with some mixing if the star is a clump star.

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I. Introduction

In an earlier paper (Böhm-Vitense and Mena-Werth 1992, abbreviated BVMW hereafter) we described a way to determine element abundance ratios from transition layer emission lines:

The surface emission line fluxes of a given element, $F_L(el)$, are given by

$$F_L(el) = Ab(el)E_{exc}(line)E_m(T) \tag{1}$$

where Ab(el) gives the abundance of the element under consideration, E_{exc}(line) gives the collisional excitation rate of the line under consideration, and $E_m(T)$ is the emission measure, defined as

$$E_m(T) = \int_{h_1}^{h_2} n_e^2 dh = \int_{T_1}^{T_2} n_e^2 \frac{dh}{d\ln T}\, d\ln T \tag{2}$$

where the integral has to be extended over the temperature range over which the line under study is emitted which usually corresponds to a change in temperature by a factor of 2. For the lines studied here the E_{exc} (line) are known either from theory or from laboratory experiments.

It is found empirically that for 20,000 K < T < 150,000 K the emission measures as a function of temperature follow a power law (see Pottasch 1963; Hartmann *et al.* 1982; Böhm-Vitense 1987). For the CII to CIV line flux ratios the abundance factor cancels out and the ratios of the line fluxes determine the ratios of the emission measures for the temperatures at which these lines originate, namely T(CII) ~ 30,000K and T(CIV) ~ 100,000K. This ratio determines the exponent in the power law for the emission measures. The emission measures for other temperatures can thus be determined. The line flux ratio of the N V (1240 Å) line to the C IV (1550 Å) line gives the element abundance ratio for nitrogen to carbon and the line flux ratio of the Si IV (1400 Å) line to the C IV line gives the silicon to carbon abundance ratio.

Such studies were done for normal main sequence stars for which we expect to find solar abundances. An abundance ratio log C/N = 0.5 represented the observations well. For the Si/C abundance ratio too large values were obtained. As discussed earlier by Hartmann *et al.* (1985) and by BVMW this was attributed to an erroneous excitation rate for the Si IV lines. BVMW determined an empirical correction for E_{exc}(Si IV) of Δlog E_{exc}(Si IV) = 0.5, if an average temperature of 74,000K was adopted for the Si IV emitting layer and if abundances of log C=8.4 and log Si = 7.65 were used with log H = 12.0. Finally a solar carbon abundance of log C = 8.5 was adopted. The Δlog E_{exc}(Si IV) should then have been 0.6 but unfortunately was not changed. We again determined this empirical correction from the best available spectra with well defined Si IV lines. From the K star spectra a correction Δlog E_{exc}(Si IV) = 0.64 $\pm$ 0.05 was found. For the Hyades F stars the same correction gives a silicon abundance of log Si = 7.76 $\pm$ 0.05. This does not seem unreasonable since the Hyades stars are believed to have a larger abundance of heavy elements (see for instance, Gratton and Sneden 1987). In the present study we used a correction Δlog E_{exc}(Si IV) = 0.6 consistent with log Si = 7.7 and log C = 8.5. A different correction would alter all our abundance ratios by a constant factor, which means in Figure 1 the zero point would be shifted. The following discussions would be unaffected.

In our previous study of giants, BVMW, we concentrated on the N/C abundance ratios but realized that the Si/C ratios also showed unexpected variations for stars at different effective temperature ranges. We suspected that the F giants with peculiar abundance ratios might be descendents of Ap stars in which the surface Si abundance has been enriched presumably due to radiative diffusion. If so this abundance anomaly should decrease with decreasing effective temperature of the giants due to deeper convection zones. By studying the evolution of the Si/C abundance ratio along the giant branch we have an opportunity to check directly whether the abundance anomalies seen for some F giants and their progenitors are indeed only surface phenomena. If so we can actually determine at which point of giant evolution the abundance anomalies disappear. This determination is one of the main results of this study. If we could determine Si abundances accurately enough and if diffusion calculations would be accurate enough we could actually determine how the depth of the convective layer changes in mass with decreasing T_{eff}.

In order to study the anomalies for the Si/C abundance ratio more carefully we have observed additional F and early G giants in the ultraviolet by means of the IUE observatory.

II. The Observations

Since for the G giants we are dealing with stars in the Hertzsprung gap we can not be choosy with the selection of target stars. The number of available stars is small and few bright stars can be found. We cannot exclude spectroscopic binaries from our sample. Also the necessary exposure times are long. Only 11 additional stars could be observed with sufficiently long exposure times. This nevertheless increases the number of F and early G giants studied by us from 18 to 29, thereby improving considerably the statistics for these spectral types.

In Table 1 we list the basic data for the newly observed stars. The previously observed stars will be included in the discussion. The Si/C abundance ratios are, however, reduced corresponding to the newly determined $\Delta\log E_{exc}$(Si IV). In Table 1 we give the excess of the silicon to carbon abundance ratios and also the excess nitrogen to carbon ratios. As outlined above these Si/C values are relative to the abundance ratios in the standard main sequence stars from which the $\Delta\log E_{exc}$ (Si IV) were determined.

We know from the earlier studies that there are several F giants with enhanced N/C abundance ratios which is not expected theoretically. It was previously suspected that such abundance changes could be due to mass transfer from unseen evolved subluminous companions as is now believed to be the case, for instance, for Ba II stars (see Böhm-Vitense, Nemec and Proffitt 1984). A white dwarf companion was indeed seen for the F6 III star HD 160365 (Böhm-Vitense 1992), for which the companion is presently separated by about 8" but was probably closer when the present white dwarf started to lose mass. For this star we were lucky that the companion happened to fall within the entrance aperture and is bright enough to be seen. Considering the small probability for this to happen there may be several more white dwarf companions for our target stars.

In the interior the increase in the nitrogen to carbon abundance ratio is presumably due to a transformation of carbon into nitrogen by the CN cycle in which the sum of nitrogen and carbon remains constant. For a given increase in the N/C abundance ratio we can calculate the decrease in the carbon abundance Δ log C with respect to the original carbon abundance. This decrease in carbon abundance leads to an increase in the observed Si/C abundance ratio. We have therefore decreased the observed log (Si/C) by Δ log C. The corrected values are listed in Table 1 as Δlog (Si/$C_\odot$). These values indicate the real change in the silicon abundance relative to the original carbon abundance, if the increase in N/C is caused by nuclear reactions, as we think is the case for the late G and K stars.

If in the process of increasing the N/C abundance ratio the sum of the carbon and nitrogen abundances was not conserved, perhaps due to the inclusion of ON processed material or of carbon enriched material, then our value for Δ log C could be in error. This might also be the case if the original surface N/C ratio is not solar as for Am and some Ap stars and their descendents if the surface carbon abundance was depleted by diffusion.

III. Discussion

a) Observational Results

In Figure 1 we have plotted the Δlog (Si/$C_\odot$) as a function of the effective temperatures T_{eff} for the stars. The temperatures were determined from the B-V colors adopting the scale by Böhm-Vitense (1981). The new measurements are indicated by the filled symbols, the previously discussed values by the open symbols. For log $T_{eff} > 3.8$ and for log $T_{eff} < 3.71$ we see a large range in Δ log (Si/$C_\odot$), with more positive than negative values. For $3.79 >$ log $T_{eff} > 3.71$, *i.e.*, for the early G stars the scatter is much smaller. The values scatter then around zero.

In Figure 2 we have plotted the Δ log (N/C) values, which means the excess abundance ratios as compared to the solar values. It is interesting to check whether increased silicon to carbon ratios are correlated with increased nitrogen to carbon ratios. If both are increased by the same factor it indicates depletion of carbon.

b) Error Estimates

IUE spectra are generally quite noisy. In addition there is always the ambiguity where to put the continuum level above which the emission in the lines should be measured. Before we can judge what Figure 1 is telling us we have to estimate the uncertainties.

On good exposures the Si IV emission line fluxes are generally judged to be uncertain by less than 0.1 dex or 25%, for the carbon line fluxes the uncertainty is judged to be somewhat less. Since the Si IV lines are formed at temperatures in between those of C II and C IV, a somewhat erroneous gradient of the emission measure due to measuring errors for the carbon lines has little influence on the determination of the Si/C abundance ratio. The worst error for this ratio will occur if both carbon line fluxes were measured too low by 0.1 dex and at the same time the Si IV flux was measured too high by 0.1 dex, (or vice versa) a rather unlikely situation. In this case the Si/C ratio might be in error by 0.2 dex at most. We consider this to be an upper limit for the uncertainty. A statistically more likely uncertainty is a value of 0.14 dex, (the square root of the sum of the squares). In Figure 1 we have drawn these error limits as dashed lines on both sides of the Δlog $(Si/C_{\odot}) = 0$ value.

c) Do we see real variations in $Si/C_{\odot}$ or only scatter?

At first sight we may be tempted to say the variations in the $Si/C_{\odot}$ ratio seen in Figure 1 are all scatter in the measurements. As discussed in the preceding section we think, however, that the upper limit for the measuring uncertainty is 0.2 dex. There are several values outside of these limits. It would also be hard to understand why the errors should be large for the high and low temperature region of the diagram while they are much smaller for temperatures between log $T_{eff} = 3.71$ and 3.81. We also realize that we find many more positive deviations than negative ones. It would also contradict statistical expectations to find most of the F and K stars having errors at or beyond the upper limits of the error. In addition there are systematic differences between stars with high values for $\Delta\log$ (Si/C$_\odot$) and those with low values: The F stars with $\Delta\log$ (Si/C$_\odot$) > 0.1 have an average v sin i = 22 ± 6.5 km/sec while those with $|\Delta\log$ (Si/C$_\odot$)$|$ < 0.1 have an average v sin i = 75 ± 22 km/sec. The F stars with high $\Delta\log$ (Si/C$_\odot$) have all v sin i below 30 km/sec. From the 8 stars with log $T_{\rm eff} > 3.8$ and $\Delta\log$ (Si/C$_\odot$) ≤ 0.15 none has v sin i below below 30 km/sec. The only F giant with low Si/C$_\odot$ abundance ratio and low v sin i is 27 Eridani, a highly variable peculiar star.

d) Our interpretation of Figure 1

For the reasons discussed in the previous section, especially the small scatter for the early G stars, we are convinced that our error estimates are generally correct and that there are true variations among the surface abundance ratios of (Si/C$_\odot$) for the population I giants. For log $T_{\rm eff} > 3.81$ we find 7 stars with $\Delta\log$(Si/C) > 0.1. Three of these stars (HD 21770, HD 175824 and 25 Mon) have no excess in N/C. We therefore conclude that the excess in Si/C is due to a surface enrichment in silicon which is inherited from the main sequence progenitors, which were probably Ap stars. Ap stars have on average smaller rotation velocities than other A stars, explaining the low v sin i seen for these stars with enhanced Si/C$_\odot$. The remaining 3 stars (HR 1889, 45 Aur and 20 Peg) have comparable excesses in Si/C and N/C. We conclude that this anomaly is probably due to surface carbon depletion as observed for many Am stars and presumably due to diffusion. These again are stars with relatively low v sin i. As expected both anomalies in the excess Si/C abundance ratios disappear when the giants become cooler and convective mixing reaches deeper.

It appears that we here observe directly the disappearance of the peculiar surface abundance anomalies which were caused by diffusion on the main sequence. At $T_{\rm eff} \sim 6500$ K mixing apparently reaches deep enough to bring back up the material which sank due to gravitational settling. This then not only proves that the peculiar high Si and low C abundances seen in the early F stars are only surface abundances, it also proves that the same is the case for their Ap and Am star progenitors. This, of course, is no new idea, but it is nice to see it directly demonstrated and to see at which point the mixing reaches deep enough to wipe out the abundance gradients.

On the negative side we find only 2 F giants with $\Delta\log \mathrm{Si/C}_\odot < 0.14$. One of these stars is 27 Eridani, a strongly variable peculiar star. The other star is λ Hor = HD 15233. We suspect it may have a subluminous evolved companion from which it collected carbon enriched material.

With the small scatter of the abundance ratios in the early G star region, confirming our error estimates, we can now also confirm that for the K stars we observe real enhancements in $(\mathrm{Si/C}_\odot)$. For these stars we see a clear separation between two groups of stars, which we have separated by the dotted line in Figure 1. Four of the 6 stars below this line are RS CVn stars showing standard values of $\mathrm{Si/C}_\odot$. Only one weak example of an RS CVn star, ϵ Ursa Majoris is found among the stars above the dotted line, but possibly also with standard $\mathrm{Si/C}_\odot$. Also found among this group is β Cephei which is very peculiar with its unusually high N/C ratio. It appears to have a normal Si abundance, though the assumption of constant N+C abundance may possibly not be correct for this star. The calculated Δ log C may then also not be correct.

An unexplained low $\mathrm{Si/C}_\odot$ abundance ratio is found for γ Hydra. Another star with low $\mathrm{Si/C}_\odot$ is the G giant 35 Cnc, a member of the Praesepe cluster. It is a very active star with a high rotation velocity (90 km/sec). HR9024, also a very active star, is near the lower error boundary for the $\mathrm{Si/C}_\odot$ ratio. All three stars have $\Delta\log$ (N/C) ratios nearly equal to their $\Delta\log$ (N/Si) ratios. The anomaly seems to be a derived high nitrogen abundance without a corresponding carbon depletion. There are several possible explanations: 1st, the N V line may be contaminated by another unidentified line, making it appear too strong. 2nd, the stars may have dredged up ON cycled material or carbon rich material after the helium flash. In the latter case, they must then now be clump stars. 3rd, the stars may have accreted carbon rich material from an unseen subluminous companion. 35 Cnc shows a strong Li I line (Wallerstein 1992) which contradicts a large amount of mixing. It speaks in favor of accreting carbon rich material.

About half of the remaining K giants show an increase of the $Si/C_{\odot}$ abundance ratio which is outside of the estimated error limits. There may be a suggestion in the data that the $Si/C_{\odot}$ ratio increases with increasing N/C abundance ratio for stars with $\Delta\log(N/C) \leq 0.55$, the theoretically expected value after the first dredge up. For larger values of N/C the $Si/C_{\odot}$ ratio does not increase any more. Our error limits are, however, too large and the number of stars studied too small to be sure of these correlations.

In our earlier paper, BVMW, we wondered whether for these temperatures an unknown line might blend with the SiIV lines and increase their fluxes. High resolution spectra showed that except for a minor contamination by a line at 1400 Å, which sometimes may contribute about 10% to the measured flux, we have not found any sign of a blend.

IV. Photospheric Abundance Determination

It is instructive to compare our results with some photospheric abundance determinations. We did such comparison in our earlier paper, BVMW, and found good overall agreement. We found indications that higher silicon abundances for some giants are also found from photospheric analysis.

In Figure 1 we have entered a few values for excess Si abundances (in comparison with the sun) determined from photospheric abundance determinations as given by Unsöld (1977) for ϵ Vir, HD 6833 and HD 122563, based on analyses by Cayrel and Cayrel (1963), Cayrel de Strobel (1966), and Wolffram (1972). We have added some additional values for K giants studied by Cayrel de Strobel (1966). Two of the giants are metal poor as indicated by asterisks in Figure 1. For these stars the excess Si abundance is given relative to the average heavy element abundance changes. There is overall agreement between photospheric results and our results. It is interesting that the result for the metal poor star HD 6833 agrees with the high Si/$C_\odot$ values found for some population I K giants in the present study.

For ϵ Virginis, the only star in common with photospheric studies Unsöld gives Δlog Si = 0.13 while we find 0.14.

V. Summary

We have studied silicon to carbon abundance ratios derived from transition layer emission lines in population I giants. The increased Si/C abundance ratios found for some F stars can be attributed to increased Si/C ratios for their main sequence progenitors, which probably were Ap stars. Some F giants seem to be descendents of main sequence stars whose atmosphere were depleted in carbon because both N/C and Si/C are increased by similar amounts. Their progenitors probably were Am stars. Both groups have low v sin i as have their progenitors.

The Si/C abundance anamoly disappears for late F and G giants as is to be expected if the excessive ratios are due to surface anomalies only, as generally believed to be the case for Ap and Am stars. When the stars evolve from F giants to G giants the depth of the outer convection zone increases as does the mixing. The surface abundance anomalies are diluted and disappear for early G giants. That this is actually observed here proves that the Ap and Am abundance anomalies are indeed only a surface phenomenon. It also demonstrates directly the increasing depth of the convection zone when the stars evolve along the giant branch.

Four of the stars studied here show a decreased Si/$C_\odot$ abundance ratio which we can only attribute to accretion of carbon enriched material from a companion when it was a mass losing luminous red giant but is now a subluminous and invisible white dwarf.

An unexplained increase in the Si/$C_\odot$ abundances occurs again in K giants for about 1/2 of the non RS CVn stars. There may be a suggestion that Si/$C_\odot$ increases with increasing

N/C for $\Delta\log(N/C) < 0.55$. More data are needed to confirm this suspicion. The RS CVn stars do not show the increased $Si/C_{\odot}$ abundance ratios.

We have at present no suggestion why for some red giants the silicon abundance appears to increase when nuclear processed material from the deep layers is mixed to the surface by deep convection.

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Table 1
Basic Data for Newly Observed Giants

Star HD	log T_{eff}	Δ log (N/C)	Δ log (Si/C)	Δlog (Si/$C_{\odot}$)	v sin i km/sec	Remark
15233	3.837	0.18	−0.14	−0.19	106	v_r var.
71243	3.837	0.18	0.14	0.09	36	
21770	3.833	−0.08	0.16	0.16	29	
23754	3.825	1.20	0.46	−0.20	6	var
175824	3.822	−0.06	0.13	0.13	50	v_r var.
79940	3.815	> −0.17	< −0.03	< −0.03	100	SB
71433	3.798	0.46	≤ 0.27	≤ 0.10	?	v_r var
160365	3.783	0.32	0.07	−0.03	82	SB, WD
150331	3.756	0.20	0.07	0.01	?	
117566	3.732	0.19	−0.03	−0.09	?	
185758	3.730	0.76	0.24	−0.09	0	

Figure Captions

Figure 1. The excess abundance ratios (compared to solar values) of silicon to the original carbon abundances are shown as a function of effective temperature. The previously determined values (decreased by 0.07 dex, see text) are indicated by open circles, the newly determined values by filled circles. The crosses and * give the abundance values determined from photospheric analyses as quoted by Unsöld (1977) and as given by Cayrel de Strobel (1966). The * refer to metal poor stars. The numbers give the rotational velocities v sin i. RS indicates an RS CVn star. FK indicates the point for FK Comae. The dotted line separates the group with mainly RS CVn stars from the other giants. The dashed lines give the estimated error limits.

Figure 2. The excess abundance ratios of nitrogen to carbon are shown as a function of T_{eff}. The well known increase for K stars is seen. Some active stars show increased N/C abundance ratios at temperatures around log T_{eff} 3.73, which means earlier than expected theoretically. The estimated error limits are again given by the dashed lines. Symbols are the same as in Figure 1. Some anomalous stars are indicated by name.

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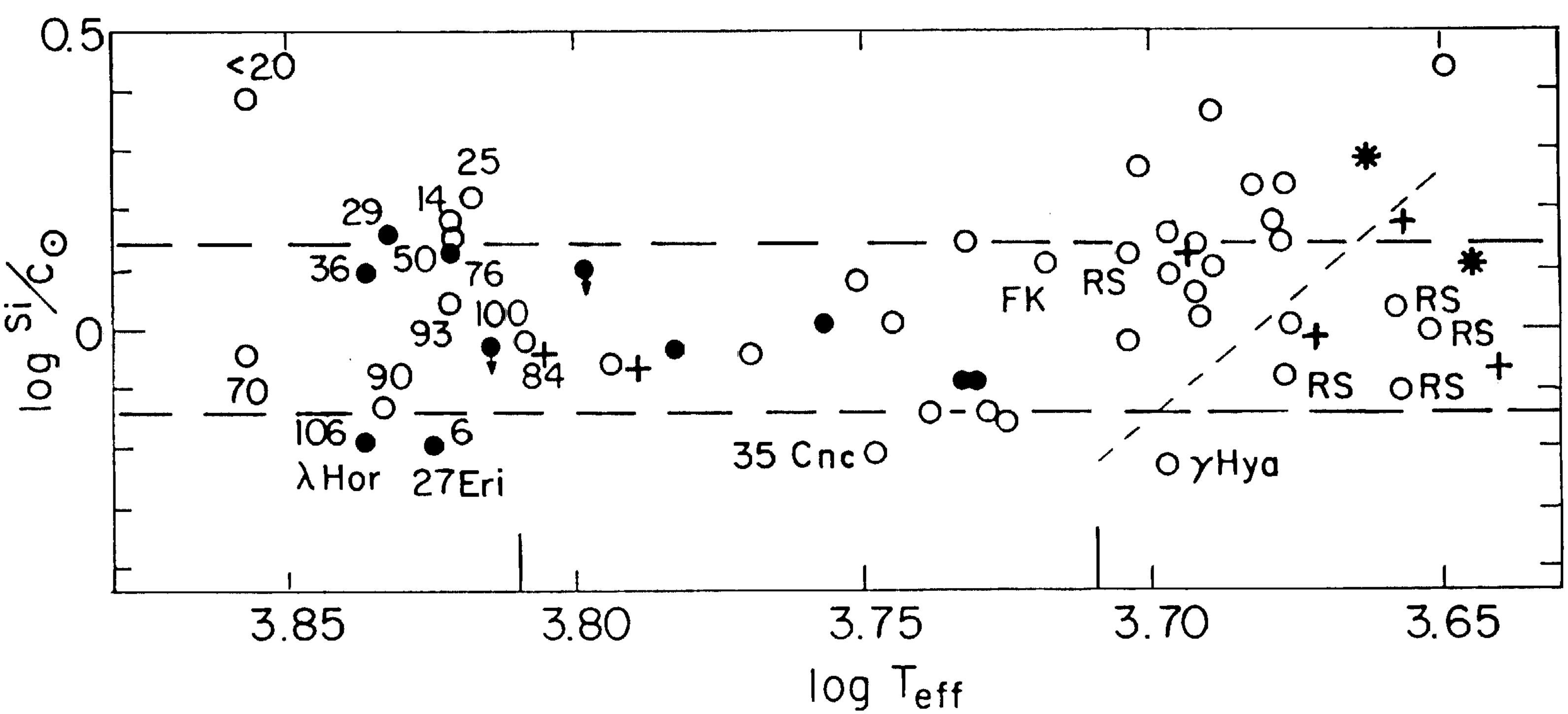

Figure 1, Böhm-Vitense

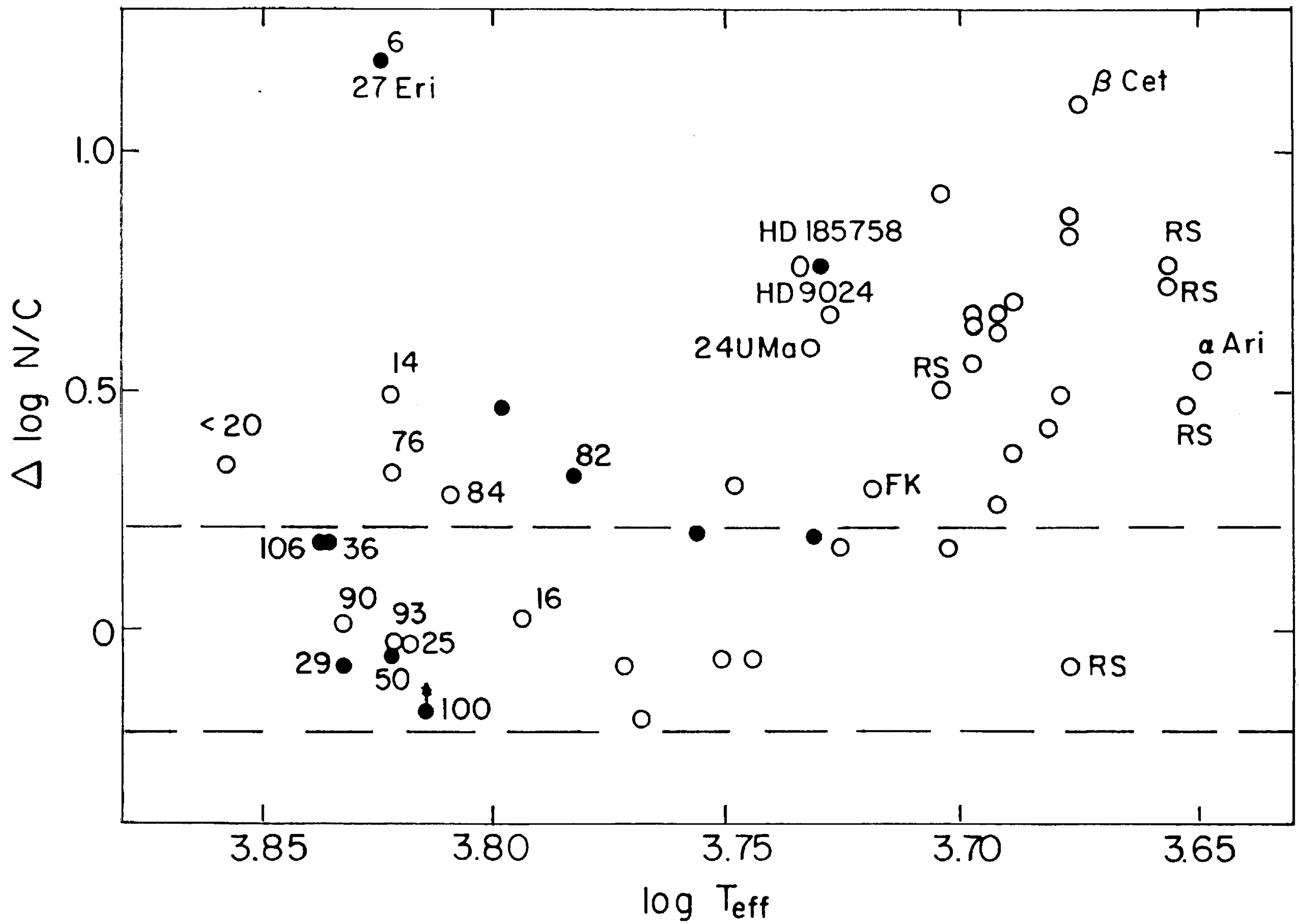

Figure 2 Böhm-Vitense