ABUNDANCE OF HELIUM IN STELLAR ATMOSPHERES

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Helium abundance in stellar atmospheres has been the subject of several recent investigations, essentially induced by progresses in the computation of non-grey model atmospheres (including line blanketing in the far U.V.), by considerable advances in the theory of Stark broadening of helium lines, by non local thermodynamic equilibrium (LTE) work for the helium spectrum and more fundamentally by the intrinsic importance of the helium over hydrogen ratio in cosmological theories.

1. Helium Abundance in Normal Population I Stars

The earliest determinations of helium abundance by Unsöld (1941 and 1944), Traving (1955 and 1957), Voigt (1952), Cayrel (1958) have consistently given a helium over hydrogen ratio by number of atoms of about 0.18. More recent determinations have given lower values: Mihalas (1964) found 0.15, Scholz (1967) 0.13, Hyland (1967) 0.10, Hardorp and Scholz (1970) 0.10. Figure 1 summarizes the results. The disquieting slope of log(He/H) versus the year of publication of the result deserves of course some comments. The discrepancy between old results and new results may be due to one or several of the following factors:

(i) Observational material,
(ii) f-values,
(iii) model atmosphere used for the analysis of the spectrum,
(iv) broadening theory used for the helium lines,
(v) line selection made for the analysis,
(vi) assumption made on line formation (LTE or else).

Point (i) has been discussed by Traving already in 1958 and again by Scholz in 1967. It is very clear from these discussions that equivalent widths used by Unsöld in 1941 and by Traving in 1955 are systematically higher than those used by Aller *et al.* (1957) or by Scholz (1967) which are based on plates of much higher resolution. If Traving (1955) had used Scholz (1967) equivalent widths he would have found He/H$\simeq$0.12 instead of 0.17.

Point (ii) deserves attention too. No better illustration can be given than comparing the helium abundance derived in 1957 for ζ Per from the 4 lines λ4009, 4143, 4387 and 4437 using the f-values popular at that time to the abundances obtained using the f-values from Green *et al.* (1966) now in general use. The He/H ratio drops then from 0.20 to 0.14 in much better agreement with recent determinations in other B stars. It is rare that oscillator strengths come out completely innocent in a discussion on abundance determination.

On point (iii) it can be said that a few results in the literature disagree because of

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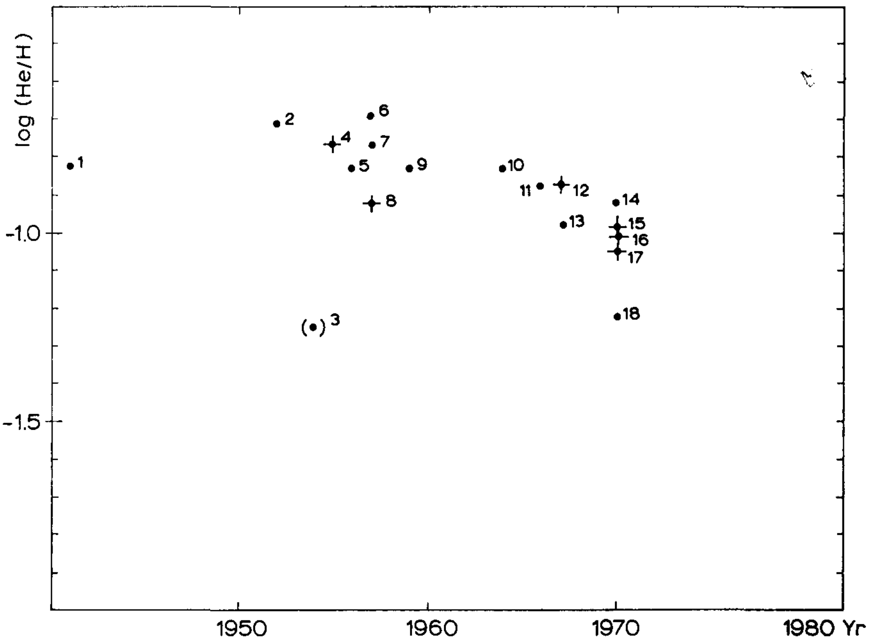

Fig. 1. Log(He/H) as a function of the year of publication of the result. Numbers give the complete reference of the paper. Crosses indicate that the object is τ Scorpii. Point seventeen is the average of 14 B stars containing τ Scorpii. Point 3 is of low weight because the effective temperature used in this paper has been subsequently proved to be much too low.

1 Unsöld, 1941 – 2 Voigt, 1952 – 3 Neven and de Jager, 1954 – 4 Traving, 1955 – 5 Aller, 1956 – 6 Cayrel, 1958 – 7 Traving, 1957 – 8 Aller, Elste and Jugaku, 1957 – 9 Aller and Jugaku, 1959 – 10 Mihalas, 1964 – 11 Underhill, 1966 – 12 Scholz, 1967 – 13 Hyland, 1967 – 14 Poland, 1970 – 15 Hardorp and Scholz, 1970 – 16 Shipman and Strom, 1970 – 18 Kodaira and Scholz, 1970.

poorly determined effective temperatures or gravities. Nevertheless in a star as τ Scorpii the occurrence of lines of different stages of ionization makes possible an excellent determination of the temperature. The gravity is not as well determined as the temperature because there are still discrepancies between theories of the broadening of the Balmer lines (Edmonds *et al.*, 1967; Kepple and Griem, 1968). Errors as large as 0.2 in $\log g$ inducing errors of the order of 10% to 20% on helium abundance can stem from this cause.

Microturbulence is generally irrelevant because thermal broadening and collisional broadening dominate microturbulent broadening for helium.

The temperature gradient is slightly different in blanketed models and unblanketed models. Fortunately the temperature distribution in a blanketed model is very like the temperature distribution in an unblanketed model of a slightly different effective temperature as shown by Hickok and Morton (1968). So as long as one does not need to know the actual effective temperature, but only to have a fair description of the variation of the temperature with depth around its value at $\tau_{4000}=0.2$, it does not matter too much.

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(iv) The broadening function of He I lines is particularly difficult to establish. The reason why is the great proximity of F and D states which has two consequences: the first one is the fact that the Stark effect merges from quadratic to linear when the perturbation reaches the separation between the F and D levels and the second one is the allowance of the otherwise forbidden nearby P–F transition by mixing of the

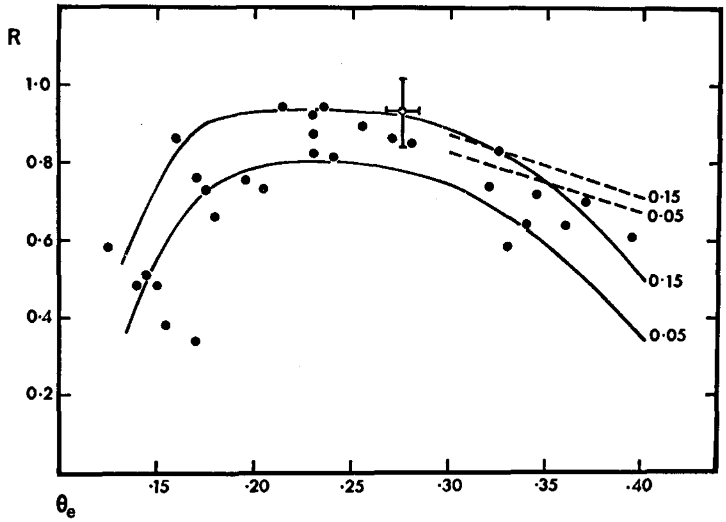

Fig. 2. The dependence of the anomaly parameter R on reciprocal effective temperature θ_{eff} for population I stars. The full lines are the computed relations for $\log g = 4.0$ models, the dashed lines those for $\log g = 3.0$. The numbers are the helium abundances by number used in the computations (from Norris thesis).

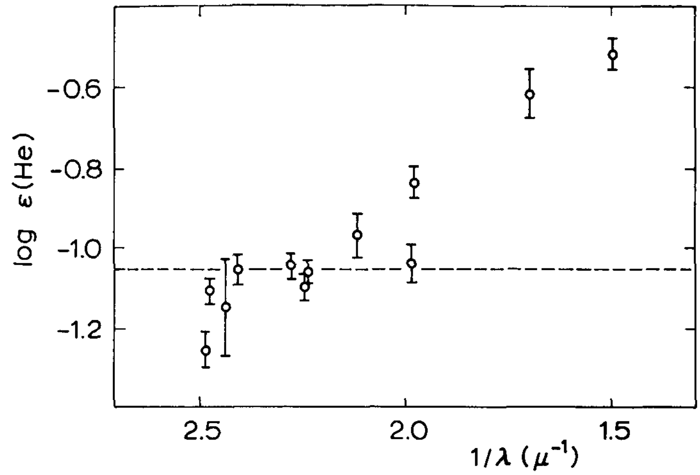

Fig. 3. Logarithmic helium abundances for individual lines as a function of inverse wavelength. The dashed curve is the mean value obtained for the sample when the lines λ4009, 5047, 5875 and 6678 are omitted (from Norris thesis).

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F and *D* states by the perturbation. Lines for which this complication does not occur are called 'isolated' lines.

Recent determinations of helium abundance from isolated lines are based on the general impact approximation theory given by Griem *et al.* (1962) which includes both elastic and non-elastic collision (see also Griem, 1964). For the two non-isolated lines λ4471 and λ4921 detailed computations have been published by Griem (1968) and by Barnard *et al.* (1969). Except for a small disagreement over the forbidden component region the theoretical profiles fit experimental profiles quite satisfactorily (Burgess and Cairns, unpublished). The exact or nearly exact broadening theory has been used by investigators to compare the variation with effective temperature of the singlet series to the variation of the triplet series. As noticed by Struve already in 1928 the singlet series and the triplet series have a different behaviour in B stars. The

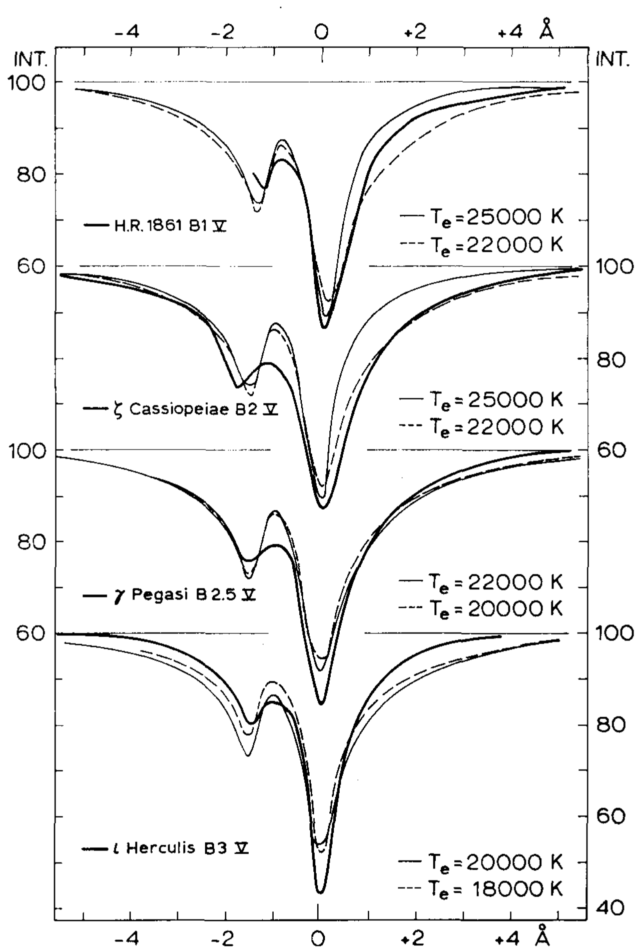

Fig. 4. Observed and predicted profiles for He I 4471 and its forbidden component (after Snijders and Underhill, 1971).

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singlet to triplet ratio (4387 to 4471 for example) increases from about 0.4 in late B's to 0.85 at the maximal intensity of He I lines and then decreases again to 0.3 or so near Bo. Two explanations have been proposed in the past to explain this behaviour. Struve suggested that it was a non-LTE dilution effect whereas Golberg suggested that it was a mere non-linear curve of growth effect. Norris (1970) has computed a parameter R, ratio of singlet to triplet equivalent widths defined by

$$R = \frac{W(4009) + W(4143) + W(4387)}{W(4026) + W(4471)}$$

and has shown (Figure 2) that the behaviour of this ratio is in fact correctly predicted by LTE-model atmospheres, ruling out the need of invoking dilution effects.

(v) Norris (1970) has derived the He/H ratio in 14 normal B stars and has shown the dependence of the result upon the line used. It is immediately obvious from Figure 3 that if different investigators use different subsets in this line sample they must be prepared to obtain discrepant results. There is one investigation based on the single line 4713 (Hyland, 1967). If the same investigation had been done with the line 6678 or 5875 all the abundances of helium would have come twice as large. The systematic trend with wavelength shown by Figure 3 could be suggestive of an erroneous continuous absorption coefficient. Such an interpretation is ruled out by the absence of slope in a similar diagram made for O II and N II lines.

There are in fact arguments to consider the red lines as more suspicious than the blue lines. They give a helium abundance which does not fit the helium abundance derived from the wings of the strong non isolated lines 4471 and 4921. The fact that recent investigators have discarded the red lines whereas former investigators have not, explains a bias favoring a higher helium abundance in earlier papers.

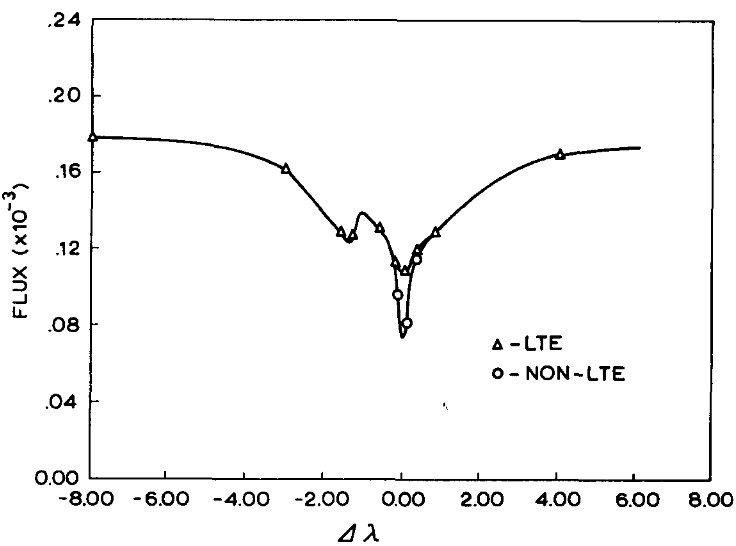

Fig. 5. Theoretical profiles for the 2^1P–4^1D transition in a 20000K atmosphere. Triangles LTE profile; circles non-LTE profile (according to Poland).

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(vi) There is some evidence that the core of strong lines is deeper than LTE predictions (Figure 4, bottom). Johnson and Poland (1969) and Poland (1970) have shown that non-LTE computations correct this discrepancy (Figure 5). The same computations also show that departures from LTE have little effect on equivalent widths of lines, in all cases smaller than 10%. This result is disputed by Underhill (1966).

It can be concluded that the lower values now found for the helium over hydrogen ratio are explainable and that further revision in the future by more than 30% seems unlikely at present.

I would personally accept the value:

$$\mathrm{He/H} = 0.10 \pm 0.03$$

and consider as real the fact that the scatter around this value in the 14 B stars analysed by Norris is small (± 0.025).

2. Abnormal Helium Content in a Few Population I Stars

We now turn our attention towards stars which are population I stars belonging to a stellar association or to an open cluster and which do not have a normal strength of their helium lines.

It was already noticed in 1952 by Sharpless that in the sword region of Orion two B stars, HD 37058 and HD 37129, had helium lines weak for their color and their otherwise line spectrum. McNamara and Larsson (1962) found two other stars in the same region and pointed out the low value of $v \sin i$ for these four objects as well as their location somewhat below the main sequence. At about the same time Sargent (1964) pointed out that the group of Ap stars was containing objects too blue for being classified A stars and that they should instead be late B stars. He suspected that the absence of He I in their spectra was due to a helium underabundance. He was then able to find the prolongation of the Ap group in B stars. Such stars are α Sculptoris (Jugaku and Sargent, 1961), κ Cancri and 3 Centauri A (Jugaku *et al.*, 1961; Hardorp, 1966). Sargent and Strittmatter (1966) have shown that the small value of $v \sin i$ and the location of weak helium stars below the main sequence could be jointly understood if these stars are intrinsic slow rotators. The weak helium stars could then be thought as a hot subgroup of peculiar stars which are also believed to be slow rotators. Garrison (1967) has added a number of new stars to this group belonging to the Sco-Cen association. Table I gives a nearly exhaustive list of weak helium line stars known at present. Twelve of them have been studied by Norris (1970) who found the following results (listed in Table II): weak helium stars are either deficient in helium by a moderate factor (of the order of two) or they are deficient by a larger factor of the order of ten. It is of course of interest to know if there is some connection between these stars and the hottest subgroups of the Ap stars. Indeed three weak helium stars are Si 4200 strong and four show phosphorus lines in their spectra like 3 Cen A. Two other ones have Sr II and Ti II. They all occur in a well limited part of the HR diagram (Figure 6).

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TABLE I
Stars that have been classified as weak-helium-line

Name	HD	Author	Group
α Scl	5737*	Jugaku and Sargent (1961)	
θ Hyi	19400	Jaschek, Jaschek and Arnal (1969)	
	21699	Garrison (1967)	α Per
20 Eri	22470	Jaschek, Jaschek and Arnal (1969)	
22 Eri	22920	Jaschek, Jaschek and Arnal (1969)	
20 Tau	23408	Huang and Struve (1956)	
	28843	Jaschek, Jaschek and Arnal (1969)	
	35298	Lee (1968)	Orion
	36540	Lee (1968)	Orion
	36629*	McNamara and Larsson (1962)	Orion
	36919	Garrison (1967)	Orion
1 Ori B	37043*	Slettebak (1963)	Orion
	37058*	Sharpless (1952)	Orion
	37129*	Sharpless (1952)	Orion
	37807*	McNamara and Larsson (1962)	Orion
12 C Ma	49333	Jaschek, Jaschek and Arnal (1969)	NGC 2287
	74196	Jaschek, Jaschek and Arnal (1969)	IC 2391
36 Lyn	79158	Searle and Sargent (1964)	
	90264	Jaschek, Jaschek and Arnal (1969)	
3 Cen A	120709*	Bidelman (1960)	Sco-Cen
3 Sco	142301*	Garrison (1967)	Sco-Cen
	144334*	Garrison (1967)	Sco-Cen
	144661*	Garrison (1967)	Sco-Cen
	144844*	Garrison (1967)	Sco-Cen
	145501	Garrison (1967)	Sco-Cen
	151346	Garrison (1967)	Sco-Cen
	162374*	Hyland (1967)	NGC 6475
	175156	Guthrie (1965)	Sco-Cen
	198513	Cowley, Cowley, Jaschek and Jaschek (1969)	
30 Cap	202671	Jaschek, Jaschek and Arnal (1969)	
	217833	Cowley, Cowley, Jaschek and Jaschek (1969)	

* Further data are given in Table II below.

TABLE II
Helium line strengths and apparent abundances for the weak-helium-line stars

Star (1)	W(4387) (2)	W(4471) (3)	n_1* (4)	n_2* (5)	n_3* (6)	ε(He) 4387 (7)	ε(He) 4471 (8)	$\Delta \log \varepsilon$(He) (9)
α Scl	180	390	2	–	–	0.025	0.020	−0.64
HD 36629	805	1550	–	2	3	0.060	0.055	−0.22
ι Ori B	75	240	3	–	–	0.005	0.005	−1.24
HD 37058	685	1210	2	2	4	0.045	0.030	−0.38
HD 37129	925	1605	1	1	4	0.085	0.060	−0.09
HD 37807	610	1245	–	2	3	0.050	0.045	−0.26
3 Cen A	320	715	2	–	–	0.015	0.015	−0.77
3 Sco	195	350	4	–	–	0.010	0.010	−0.94
HD 144334	160	220	2	–	–	0.010	0.005	−1.09
HD 144661	145	270	2	–	–	0.010	0.010	−0.94
HD 144844A	⩽ 30	105	3	–	–	⩽ 0.005†	0.005†	⩽ −1.24
HD 162374	210	480	5	–	–	0.010	0.015	−0.85

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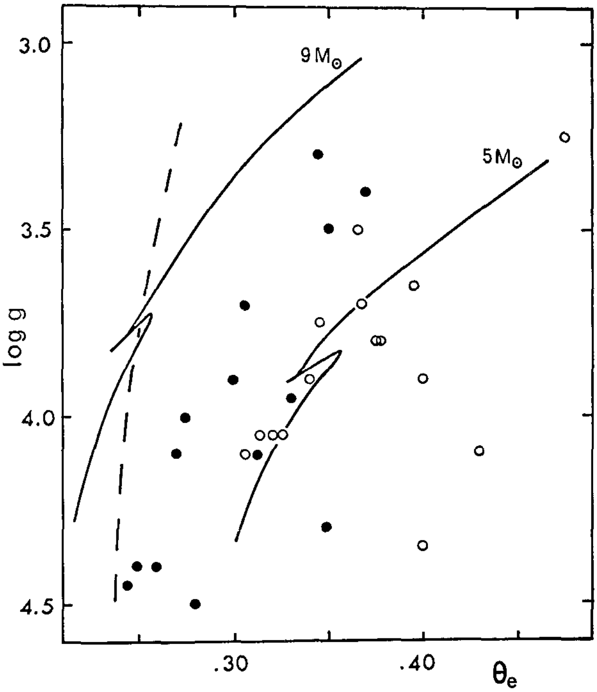

Fig. 6. The positions of the weak-helium-line stars (filled circles) and the Si 4200 stars (open circles) in the (θ_{eff}, $\log g$)-plane. The continuous lines are the evolutionary tracks of 5 and 9 $M_{\odot}$ stars. The dashed line corresponds to the boundary at which the helium in the stellar atmospheres is 90 %> ionized at an optical depth $\tau_{4000} = 0.2$. (From Norris, 1970).

3. Helium in Population II Stars

It was known already in 1956 (Münch, 1956) and strongly realized in 1966 (Greenstein and Münch, 1966, Sargent and Searle, 1966) that both blue horizontal branch stars and similar population II field stars, much easier to observe, were helium weak. From a quantitative discussion of the dependence of helium line strengths on effective temperature, gravity and helium abundance these authors concluded that a helium deficiency as large as a factor of 10 was needed in such objects.

Nevertheless, Traving (1962) analysing two halo subdwarfs BD+33°2642 and Barnard 29 in M 13, found a normal helium content for the first object and a moderate, possibly not significant, deficiency for the second star. Stoekly and Greenstein have confirmed Traving's result for Barnard 29 quite recently.

Recently Norris (1970) has studied the subdwarf HD 205805 and found it helium deficient by a factor of 10 (see Table III). The data obtained by Sargent and Searle (1968) for the three stars Feige 11, 34 and 65 are interpreted by Norris as indicating a helium deficiency by as much or more.

Newell (1970) finds the blue horizontal branch stars S-18 in Messier 15 to be helium deficient by at least a factor of ten.

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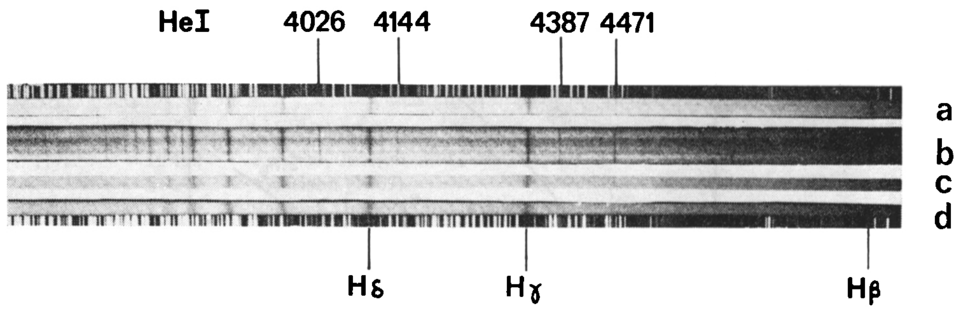

Fig. 7. Feige 65 (a), Feige 11 (c) and Feige 36 (d) are compared with τ Scorpii (b). The Balmer lines are broader in the spectra of the Feige stars than in τ Sco. This is interpreted as a gravity effect. All the helium lines in the Feige stars are exceedingly weak as compared with τ Scorpii (after Sargent and Searle, 1966).

TABLE III

Helium abundances for HD 205805 and γ Pegasi from individual lines

λ(Å) (1)	N(He)/N(H) HD 205805 (2)	γ Pegasi (3)		Δ log N(He)/N(H) (HD 205805 – γ Pegasi) (4)	
4009	⩽ 0.03		(0.07)		(⩽ −0.4)
4026	0.01	0.15	(0.10)	−1.2	(−1.0)
4120	⩽ 0.006	0.4	(0.16)	⩽ −1.8	(⩽ −1.4)
4143	⩽ 0.025	0.12	(0.10)	⩽ −0.7	(⩽ −0.6)
4387	0.007	0.21	(0.07)	−1.5	(−1.0)
4437	⩽ 0.026	0.22	(0.10)	⩽ −0.9	(⩽ −0.6)
4471	0.015	0.16	(0.10)	−1.0	(−0.8)
4713	0.024	0.13	(0.10)	−0.7	(−0.6)
4921	0.015	0.21		−1.2	
5015	0.015	0.05	(0.09)	−0.5	(−0.8)
5047	0.034		(0.19)		(−0.8)

The situation was therefore somewhat unclear when a big discovery was made by Sargent and Searle in 1967. It is fair to acknowledge here the large and remarkable contribution of these authors to the topic. Studying the spectrum of the field blue horizontal branch star Feige 86 at a dispersion somewhat higher than what was done before, namely taking a 6 hr exposure at 9 Å/mm at the 200″ Hale telescope, they discovered many sharp weak lines never seen before. They were able to identify these lines with P II and to see that $v \sin i$ was smaller than 12 km/sec for this star. All these features were reminiscent of the peculiar spectrum of 3 Cen A (including helium weakness) and the first evidence that the horrible mess in abundances occurring in population I A and late B stars had crept into population II objects located in a similar region of the H–R diagram and having a low rotational velocity. The authors were also able to see that other Feige stars obtained with a lower dispersion showed P II lines at the limit of detection.

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This new finding was opening the possibility that helium deficiency so often reported in population II hot stars was not necessarily to be taken as indicative of a low primordial helium abundance in the material from which the stars formed. This deficiency could be as well of a similar origin as the one depleting helium in some population I peculiar objects. Unfortunately the mechanism depleting helium and enhancing phosphorus in these stars is not better known for population II stars than for population I stars.

Interesting attempts to explain these peculiarities by gravitational settling or coronal evaporation have been made but no quantitative theory of them has been successful yet.

4. Helium Stars

Helium stars are a group of high velocity stars defined by Klemola (1961) and showing almost no hydrogen lines in their spectra. The atmospheres of a few of these stars have been analysed by Hill (1965) and more recently one of them, BD+10°2179, has been studied very deeply by Hunger and Klinglesmith (1969). The helium over hydrogen ratio is found to be of the order of 10^4 or larger. Carbon is strongly overabundant (by mass) and oxygen deficient. It is very unlikely that this chemical composition has anything to do with the chemical composition of the matter out of which the star was formed. They are very evolved objects having probably undergone hydrogen and helium burning and which have succeeded in getting rid of their hydrogen shell. Much less extreme cases of helium richness are known in low velocity stars (population I) as σ Ori E studied by Klinglesmith *et al.* (1970). This star has a He/H ratio by number equal to 1.5 corresponding to $X \simeq 0.28$; $Y \simeq 0.70$.

A rather unique case is the extremely low gravity metal poor star BD+39°4926 studied by Kodaira *et al.* (1970) and which may have He/H$\simeq$1 with a low effective temperature of 7500 K.

TABLE IV

Equivalent widths and differential helium abundances of *a* Centauri compared with χ Centauri for the phases 0.50, 0.63, 0.83, 0.00

λ	Transition	W(mA)				$\Delta \log \varepsilon$(He) (a Cen $-\chi$ Cen)				$\varepsilon(\mathrm{He})_{\chi\,\mathrm{Cen}}$
		$\phi=0.50$	0.63	0.88	0.00	0.50	0.63	0.88	0.00	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
5015	2^1S–3^1P	–	70	270	–	–	−1.07	−0.15	–	0.070
4437	2^1P–5^1S	⩽20	⩽30	145	215	⩽−1.17	⩽−0.91	−0.10	0.33	0.090
6678	2^1P–3^1D	200	330	820	1000	−1.35	−0.95	−0.07	0.08	0.310
4387	–5^1D	90	180	1080	1480	−1.50	−1.20	0.18	0.51	0.095
4143	–6^1D	90	240	1180	1550	−1.42	−0.98	0.16	0.43	0.105
4009	–7^1D	30:	110	940	1250	−1.48	−1.00	0.25	0.48	0.060
4713	2^3P–4^3S	75	95	325	420	−1.11	−0.95	0.07	0.38	0.090
5875	2^3P–3^3D	350	440	930	1160	−1.03	−0.83	0.01	0.21	0.170
4471	–4^3D	320	480	1800	2320	−1.28	−1.03	0.14	0.42	0.075
4026	–5^3D	320	520	1880	2300	−1.30	−1.06	0.10	0.34	0.080

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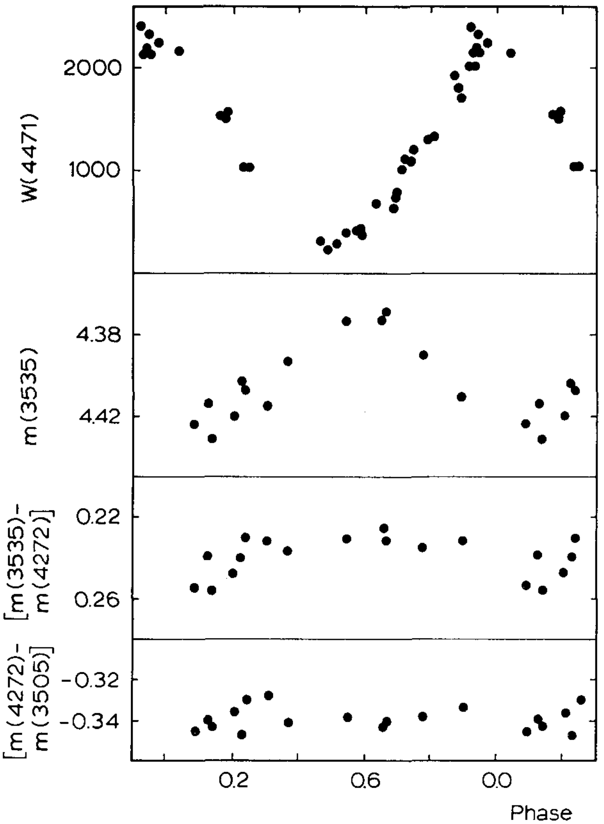

Fig. 8. Comparison of narrow bands measures with the helium line variation in *a* Cen. The upper curve is the variation of the line He I 4471, the next three are the continuum magnitude m (3535) and the two colours [m(3535)-m(4272)] and [m(4272)-m(5305)]. (From Norris, 1970).

5. The Star a Centauri

The most astonishing star in the sky regarding the behaviour of its helium spectrum is a Centauri. This star found by Bidelman (1965) manages to be periodically helium poor, helium normal and helium rich in the time span of 8.81 days (Table IV). One would like to know of course what else happens in this star. Surprisingly, not very much. Figure 8 shows that the magnitude of the star varies by only 0.06 mag. in the UV and that its colour varies still less. Lines of other elements have much smaller variation than the helium lines, not in phase with them, or no variation at all. Si III 4532 varies whereas Si II 4130 does not. Norris (1970) has shown that these variations of the rest of the spectrum could not be understood as a secondary effect of a prime strong variation in helium content.

6. Conclusion

The helium over hydrogen ratio as derived from stellar spectra ranges from 0.005 in

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many population II stars and a few weak helium population I stars to 10^4 or more in helium stars.

The average value of the helium over hydrogen ratio in population I is well defined and equal to 0.10 ± 0.03. This value has little scatter within 300 pc from the Sun.

The origin of helium deficiency occuring in a few population I stars and more commonly on population II stars is not clear yet. Any inference from this helium weakness on the primordial helium content of the matter in which the star originated is open to question since abundances in Ap star atmosphere can hardly be taken as representative of the present interstellar matter.

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DISCUSSION

David S. Leckrone: Most of the studies of population I main-sequence stars discussed by Professor Cayrel were based upon the exclusive use of equivalent widths of the He I lines. I have recently completed a study primarily to determine to what extent one can fit the observed profiles of the He I lines with theoretical profiles, calculated by use of the most recent line broadening theories on the assumption of LTE. I have considered eleven different He I lines as observed in high dispersion spectra of seven main-sequence stars, covering the spectral type range B0-B9. Four of the lines considered are hydrogenic, seven are isolated.

The first slide illustrates the comparison between theory and observations for eight He I line profiles for the B1 star HR 1861. Clearly, for most of the lines shown one *cannot* simultaneously fit the observed line wings and the observed line cores with the theoretical LTE profiles. A reasonable fit can be obtained in the wings, but the discrepancy between theoretical and observed profiles becomes progressively worse as one approaches the line center.

This is not a particularly surprising result at this early spectral type. Similar results have recently been reported by Hardorp and Scholz for two B0 stars. What is of particular interest here is that, for some of these lines, the problems in fitting the observations with LTE theoretical profiles appear to persist over the entire range of B spectral types. The next slide illustrates the nine He I line profiles for π Ceti, a B7 star. This is a rather cool star as B stars go, but even here the cores of λ 4471 and λ 5876, and possibly also of λ 4026 and λ 4388, cannot be matched with LTE theoretical profiles.

I was able to obtain estimates of the helium-to-hydrogen ratio for six of the stars investigated, primarily on the basis of the weaker He I lines and the wings of the strong lines, where reasonable theoretical fits were obtained. The average value of N(He)/N(H) obtained for the six stars, from a total of 46 He I lines, is 0.106. The scatter in the abundances from line for a given star was quite low and there was initially no scatter in the abundances derived from star to star over the spectral type range B7-B0. The question of the physical significance of the abundances I have derived must ultimately rest on a rigorous test of the LTE assumption for the atmospheric regions where the weak He I lines and the wings of the strong lines are formed. I believe Miss Underhill will have more to say on this point shortly.

Anne B. Underhill: In the line-forming layers of main-sequence early type atmospheres the electron density lies in the range 10^{13} to 2×10^{14}. This means that there are not enough collisions to maintain LTE level populations and that the actual populations occurring are governed by a complicated balance between radiative and collision processes.

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There are two results:

(1) The source function in the line is not identical with the Planck function,

(2) The optical depth scale in a line frequency, which depends on the number of atoms in the lower level of the atom, may be significantly different from that deduced using the hypothesis of LTE.

The first result gives He I lines from 2^1P and 2^3P which may be up to 15% deeper in the center than calculated by LTE.

The second result directly affects abundance determination of helium because relative abundances are obtained by intercomparing the optical-depth scales in lines of different elements.

By using the curve of growth or by fitting line wings one estimates [N(He)/N(H)] $[b_{\mathrm{He}}(2^3P)/b_{\mathrm{H}}(n=3)]$ from the triplets and [N(He)/N(H)] $[b_{\mathrm{He}}(2^1P)/b_{\mathrm{H}}(n=3)]$ from the singlets.

Exploratory calculations for a layer with $T_e = 15000°$, $N_e = 10^{14}$ and the radiation field represented as 0.5 B (T_{rad}) gives for He I:

$T_{\mathrm{rad}} = 15000°$		$T_{\mathrm{rad}} = 10000°$	
level	b_{He}	level	b_{He}
1^1S	2.67	1^1S	2.02×10^3
2^3P	1.68	2^3P	20.8
2^1P	1.34	2^1P	0.732

Since $b_{\mathrm{H}}(n=3)$ is about 1.1, when T_{rad} is 15000 K one may overestimate the relative abundance of helium to hydrogen by 15 to 40% if one assumes LTE (that is, if the ratios of all departure coefficients are assumed to be unity).

If the radiation at wavelengths shorter than 584 Å is particularly deficient and thus can be represented by a radiation temperature of 10000°, the overestimate of the helium abundance will be larger.

Roger Cayrel: The dilution effects you have pointed out are taken into account in the Johnson and Poland (1969), Poland (1970) and Milhalas and Stone (1968) computations. Their conclusion is that the departure from LTE is not larger than 10%. It means that the actual radiation field in stellar atmospheres is better fitted to the local temperature (or conversely) than in the example you have given at the blackboard.

The errors I give for the abundance of helium on population I normal B stars allow for this non-LTE effect.

A. Underhill: The singlet-triplet anomaly as defined by Struve was something seen by visual inspection of spectrograms and thus is chiefly determined by differences in central depths of the lines. Struve's observations receive beautiful confirmation when a correct physical theory of the helium is used. The hypothesis of LTE is too rigid and gives only an indication of the complex variations which occur. It does not do full justice to the details of what is observed.

Carl A. Rouse: In *Astron. Astrophys.* 3, 122 (1969), I reported that with an assumed ratio of helium to hydrogen, N(He)/N(H) = 0.14 (Y = 0.35), a solar-model photosphere predicted continuum intensities at 4000 Å in agreement with the mean of observations. I now wish to report that these results, when corrected with the line absorption opacity factor determined by H. Holweger (*Astron. Astrophys.* 4, 14, 1970) yield continuum intensities of 4.43×10^{14} erg/cm² sec ster Å at 4000 Å and 4.22×10^{14} at 5000 Å. This new theoretical value at 4000 Å is in excellent agreement with the observations of J. Houtgast (Proc. Academy Amsterdam, Series B, 68, No. 5, 1965); and at 4000 Å and 5000 Å, in very good agreement with the observations of Labs and Neckel (cf. first two references above), and of Mulders (reported in the first reference above).

Consequently it is concluded that the most probable solar photospheric helium abundance for the present Sun is about 35% by mass (N(He)/N(H) = 0.14), and is probably greater than about 30% (N(He)/N(H) = 0.10) and less than 40% (N(He)/N(H) = 0.17). More calculations are needed to set upper and lower limits.

J. C. Pecker: Would Cayrel comment on the helium abundance in the solar atmosphere, including determinations through space studies, and on the sensitivity of continua to the He content?

As far as Dr. Rouse's results are concerned, my feeling is that the continuum of the solar spectrum depends too little upon the helium content to lead to a unique determination.

C. Rouse: I wish to point out that the intensities of radiation predicted by solar-model photospheres are quite sensitive to the assumed abundance of helium. A model photosphere with an assumed helium abundance of 17% by mass (N(He)/N(H) = 0.05) yielded continuum intensities about a third of the values obtained with Y = 0.35 (N(He)/N(H) = 0.14), which might suggest an approximate linear

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variation with N(He)/N(H), i.e. a linear variation with the hydrogen abundance, but with a negative slope. (A more detailed discussion of my work is in press in *Vol. 4* of *Progress in High Temperature Physics and Chemistry*, Pergamon Press.)

I think, perhaps, that Dr. Pecker has in mind more distant stars where g, the effective gravity, is not known, and hence also becomes a parameter in the photospheric model.

R. Cayrel: I have *not* included in this review talk any result concerning the Sun because the great complexity of the chromosphere (inhomogeneities, large departures from LTE) makes any determination of helium/hydrogen ratio much more difficult and uncertain.

The determination of the He/H ratio from the continuum is possible in helium rich stars (like σ Ori E) in which the jump at 3422 Å is measurable. It is very impractical in normal B stars.

D. D. Burgess: I should like to comment on attempts to fit the $2\,^3P$-$4\,^3F\,\lambda$ 4470 intensities in model atmosphere calculations. Even the most recent line broadening theories (e.g. Griem, 1969) predict forbidden component intensities for He I 4471 which are too high by an amount exceeding 30% in comparison with laboratory observations. (D. D. Burgess and C. J. Cairns, *J. Phys. B.*, July 70). Similarly, experimentally the intensity between the allowed and forbidden lines is too *high* in comparison with theory – again somewhat reminiscent of the stellar results. These discrepancies are expected to get worse with increasing temperature and decreasing density, and I suggest one does not worry too much about fitting model atmosphere calculations to observations for these forbidden lines until such a data as the line-broadening theories improve in this respect.

R. Kippenhahn: Why is it that we do not believe the helium content of stars if it is, say, variable in time, but we do believe it if the content is 'normal'?

R. Cayrel: The star a Cen is not related to any group of variable stars.

One possible, but objectionable, explanation could be that the star had in the past a companion which has exploded and has spread a great deal of helium over one hemisphere of the star.

But the hemisphere should be seen with practically no obliquity now from the Earth, and there is no supernova remnant around the star. Also the smallest differential rotation of the star (such as that observed on the Sun) would have smoothed out any regions of high helium abundance.

A. Underhill: I should like to give another answer to Kippenhahn's question. As I said before, normal methods of analysing stellar spectra give you a value for the product $[N(He)/N(H)]\cdot(b_{He}/b_H)$, where the b's are the population parameters for the lower level of the line observed. True abundance ratios can be found only when it is possible from other considerations to evaluate the ratio of the b's. Typical values for the b's are shown in my prepared comment above. It is clear from numerical experiments that the b's for the observable lines may range through numbers from 0.5 to 20 or more, depending on how much radiation is available at wavelengths which will lift atoms out of the ground level $1\,^1S$. This means radiation with $\lambda < 584$ Å.

Stars in which the He I lines vary may be demonstrating a change in the very short wavelength spectrum due to 'stellar activity'. It is not necessary to adopt *ad hoc* models of oblique rotators with areas of differing temperature and pressure i.e. 'star spots'. Star spots are not excluded either. Postulating star spots does not get at the physical roots of the problem of spectrum analysis.

R. V. Wagoner: Has any star been observed to have weak helium but no relative abundance abnormalities among the heavier elements?

R. Cayrel: There are Population I stars which show weak helium and no other abundance abnormalities.

A. Przybylski: Recently I made the determination of helium in two metal-poor stars HD 106304 and HD 32034. In both stars metals are deficient by a factor of 6–8 ($\Delta \log N_{Me} = 0.8$–0.9). Helium is normal in both.

HD 106304 is a horizontal branch star with high space velocity. Its spectral type is A0.

HD 32034 is the second brightest star in the Large Magellanic Cloud. Its spectral type is B9 or A0.

R. Cayrel: I have perhaps not made it clear enough that helium weakness in population II, although frequent, is not always present. The star Barnard 29 (in M13), for example, analyzed by Traving in 1962 is not helium poor. Several other examples of this type are known in field halo stars.

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