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Abundances of the ^{3}He star 3 Cen A (B5 IIIp) from ultraviolet IUE spectra*

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Abstract. High resolution (0.010-0.025 nm) IUE ultraviolet spectra of the peculiar ^{3}He star 3 Cen A were analyzed in the whole 120-320 nm region. Abundances were derived from the comparison of the observed and computed spectra. For computing spectra a Kurucz ATLAS9 model with parameters $T_{\rm eff}$=17500 K, $\log g$ = 3.8, and microturbulent velocity ξ=0 km s^{-1} was adopted. A rotational velocity v*sini*=0 km s^{-1} was assumed. Colour indices, flux distribution, ultraviolet Si lines, and Balmer profiles were used to fix the model parameters. The observed spectra are reproduced at best with the following abundances: He [-0.55], B [-1.0], C [-0.75], N [-0.5], Mg [-0.5], Al [-1.5] underabundant, P [+1.6], Sc [+1.0], Mn [+1.4], Cu [+2.0] overabundant, Ga [+3.25], Kr [+3.3], Hg [+4.5] extremely overabundant.

The comparison of the ultraviolet spectrum and of the abundances of 3 Cen A with those of the normal B-type star ι Her and of the Pop II peculiar B-type star Feige 86 has shown that the same elements contribute to the line spectrum of ι Her and 3 Cen A even if with different abundances, so that the spectra can be compared. In the case of Feige 86, the overabundance of heavy elements which are not observed in 3 Cen A (i.e. Pt II, Pt III, Au II, Au III, probably Mo III), the lower overabundance of Ga [+1.0], and the larger underabundance of the light elements C [-2.5] and N [-2.0] make the ultraviolet line spectra of Feige 86 somewhat different from those of both ι Her and 3 Cen A. Also the He I lines have different profiles in the two peculiar stars, although He is underabundant in both.

With the specific abundances of 3 Cen A we computed an opacity sampling ATLAS12 model having the same parameters as the ATLAS9 model. We found that the energy distribution from the ATLAS9 model and solar abundances is not very different from that derived from the ATLAS12 model, the synthetic spectrum approach, and the specific abundances of 3 Cen A.

Key words: stars: abundances – stars: chemically peculiar – stars: individuals (3 Cen A, Feige 86, ι Her) – ultraviolet: stars

1. Introduction

3 Cen A (HD 120709, HR 5210, V=4.56^{m}) is a southern B5 III-IV Pop I peculiar star which belongs to the Scorpio-Centaurus association and is the brighter member of a visual double system. The companion, which is 8" distant, has a spectral class of B8 V and V=6.1^{m}. 3 Cen A is classified as a He-weak star belonging to P-Ga subgroup.

The star was extensively studied in the sixties when Bidelman (1960) first observed spectral lines of P II and P III of unusual strength. Sargent & Jugaku (1961) pointed out an anomalously high concentration of ^{3}He, and Jugaku, Sargent & Greenstein (1961) and Jugaku & Sargent (1963) confirmed the abundance anomalies for several elements observed in the 310-860 nm region. On the basis of a curve of growth analysis, helium and oxygen were found to be deficient by a factor of about 6, with He present mostly as ^{3}He. Nitrogen, phosphorus, iron, gallium, and kripton were found to be overabundant by factors of about 5, 100, 4, 8000, and 1300 respectively. The abundances of carbon, neon, magnesium, silicon, calcium, and argon were found to be close to the solar ones. Later on, fine analyses performed by Hardorp (1966) and Hardorp, Bidelman & Prölss (1968) yielded abundances in good agreement with those derived from all the previous coarse analyses. Hardorp et al. (1968) adopted an unblanketed model with parameters $T_{\rm eff}$=18150 K, $\log g$ = 3.7 and a microturbulent velocity $\xi \leq$ 2 km s^{-1}.

Hack & Stalio (1975) extended the analysis of 3 Cen A to the ultraviolet region and studied U1 (0.005 nm resolution), U2 (0.02 nm resolution), and V2 (0.04 nm resolution) Copernicus spectra. The high resolution U1 spectrum covers the regions 106.4 - 106.7, 108.2 - 108.6, 114.4 - 115.19 nm, and 118.9 - 119.7 nm. The U2 and V2 lower resolution spectra cover the

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* Based on observations by the International Ultraviolet Explorer (IUE)

107.0-131.2 nm and the 211.9-260.4 nm regions respectively. The U2 spectrum has a resolution lower or comparable to that of the IUE high-resolution shortwavelength range. The resolution of the V2 spectrum is half of that of the high-resolution IUE spectra observed in the same region. Hack & Stalio (1975) determined preliminary identifications and abundances. However, Copernicus spectra were not further used by them to perform a definitive analysis owing to the very short scans obtained with the U1 photomultiplier, which did not permit them to fix a reliable level for the continuum, and because the U2 and mostly V2 spectra were considered to be of lower quality than the high-resolution IUE spectra just observed after year 1979. Since the Hack & Stalio reduced data have been lost, and since the data would not be an improvement if we rereduced them, we here use only the IUE data.

This paper is a study of high resolution IUE ultraviolet spectra of 3 Cen A in the whole 120-320 nm region by using the spectral synthesis method with the Kurucz (1993a) models and mainly the Kurucz (1993b) line list. In this way we derived abundances for several elements not observed by Jugaku et al. (1961) in the visible region. The aim of this investigation was mostly the comparison of the ultraviolet spectrum of 3 Cen A with the ultraviolet spectrum of the horizontal-branch Pop II peculiar star Feige 86 (BD +30 2431; B3 V). Because studies of the optical region showed that 3 Cen A has the same type of peculiarities of Feige 86, even though these two stars belong to different populations, we wanted to verify whether this similarity may be extended also to the ultraviolet. The ultraviolet spectrum of Feige 86 was extensively studied by Bonifacio et al. (1995).

The normal B-type star ι Her (HD 160672, HR 6588, B3 IV) was used as comparison star. We updated the analysis of ι Her performed by Castelli & Bonifacio (1990) in that we used more recent Kurucz models and extended the analysis also to the IUE long-wavelength region.

Finally, we computed an opacity sampling ATLAS12 (Kurucz,1996) model for 3 Cen A by using the opacities which correspond to the specific abundances of the star. We compared the energy distribution from the ATLAS9 model and solar abundances with the energy distribution from the ATLAS12 model, a synthetic spectrum approach and the specific abundances of 3 Cen A. No significant differences have been found.

2. The data

Four SWP and six LWR IUE high resolution (HR) spectra of 3 Cen A taken from the IUE archive at Vilspa were examined. Details of the images are given in Table 1. We selected the images SWP 3950 and SWP 14945 in the short-wavelenght region and the images LWR 11508 and LWR 11520 in the long-wavelength region as the best ones to be anayzed, on the basis of the quality of their exposition and signal to noise ratio. They are marked in Table 1 with an asterisk. Table 1 lists also the spectra of the comparison stars ι Her and Feige 86 which were analyzed.

Table 1. Spectra of 3 Cen A and of the comparison stars Feige 86 and ι Her.

Star	image	aperture	t_{exp} (sec)	obs date	Observer
3 Cen A	SWP3949	S	179	19 Jan 1979	Jugaku
	SWP3950*	S	210	19 Jan 1979? R	Jugaku
	SWP14945*	S	300	25 Mar 1981	Jugaku
	SWP30546	L	195	16 Mar 1987	Freire
	LWR3521	S	209	19 Jan 1979	Jugaku
	LWR11501	S	130	3 Mar 1981 R	Jugaku
	LWR11502	S	180	25 Mar 1981 R	Jugaku
	LWR11508*	S	150	25 Apr 1981	Jugaku
	LWR11509	S	240	25 Apr 1981	Jugaku
	LWR11520*	S	150	25 May 1981	Jugaku
ι Her	Copernicus spectra (122.8-146.7 nm)				
	SWP5720	S	79	1979 R	Leckrone
	SWP3243	S	52	311 1978 R	Leckrone
	LWR4949	S	49	186 1979 R	Leckrone
	LWR2845	S	49	311 R	Leckrone
Feige 86	SWP15595	L	17580	29 Nov 1981 R	Selvelli
	SWP20127	L	14700	153 1983	?
	LWR11155	L	7620	27 Jul 1981 R	Koepper

R=reprocessed images
* = images of 3 Cen A used for the analysis

Table 2. The nominal resolution both in Å and km s^{-1} of the IUE images

λ	SWP(old)		SWP(new)		LWR(old)		LWR(new)	
nm	Å	km s^{-1}	Å	km s^{-1}	Å	km s^{-1}	Å	km s^{-1}
130	0.10	23.10	0.09	20.75				
160	0.13	24.35	0.12	22.48				
180	0.17	28.31	0.16	26.64				
200	0.19	28.48	0.19	28.48	0.17	25.5	0.15	22.5
240					0.18	22.5	0.16	20.0
280					0.21	22.5	0.17	18.2
310					0.24	23.2	0.19	18.4

The analyzed images were normalized to the continuum by using the interactive code NORMA written by Bonifacio (1989).The procedure permits one to choose several continuum points in each order. Then, smooth interpolated stable curves through these points are obtained by means of Hermite spline functions (subroutine INTEP by Hill (1982)). Each order in each spectrum was normalized independently and then the normalized orders were compared by superimposing the two normalized images.

The resolution of the IUE images depends on the version of the IUESIPS code used to process the images. The nominal resolutions related with the old and new software are given in Table 2 (from Imhoff, 1984). Old software is that before 10 November 1981.

3. The atmospheric parameters of 3 Cen A

For B-type stars the stellar parameters $T_{\rm eff}$ and $\log g$ can be derived from the Strömgren indices c and β, from the energy distribution, from high-resolution line profiles, and from ionization equilibria of the relevant ions present in different ionization states. Each method suffers from uncertainties related both with the data and the models. Castelli (1991) discussed how synthetic grids of Strömgren indices computed by different people may yield different parameters and showed that parameters derived from the photometry may differ from parameters derived from spectrophotometry, in spite of the same atmospheric models are used. In addition, reddening is a rather intriguing quantity when photometric and spectrophotometric observations are used.

Next subsections deal with the model parameters of 3 Cen A derived from different methods. Table 3 summarizes the results.

Table 3. $T_{\rm eff}$ and $\log g$ for 3 Cen A from different methods

(b-y) (b-y)$_o$	m1 m$_o$	c$_1$ c$_o$	β	E(b-y) E(B-V)	Ref	$T_{\rm eff}$ (K)	log g
T_{eff} and log g from Strömgren photometry							
-0.062	0.096	0.251	2.638	0.025	1		
-0.087	0.104	0.246		0.034		17900±250	3.57±0.02
-0.062	0.108	0.315	2.704	0.018	2		
-0.080	0.114	0.312		0.024		16440±250	4.29±0.02
			2.683		3	(17680±250)	4.24±0.02
			2.704		4	(17630±250)	4.51±0.02
T_{eff} from visual spectrophotometry for log g=4.3							
				0.00		17500	
				0.02		17750	
				0.03		18000	
T_{eff} from UV Si profiles for log g=4.3							
						17500	
log g from Balmer profiles for T_{eff}=17500 K							
					5		3.7
					6		3.8

(1) Cameron (1966); (2) Crawford et al. (1970), (3) Stokes (1972);(4) Strauss & Ducati (1981) (5) Sargent & Jugaku (1961); (6) Norris (1971)

3.1. $T_{\rm eff}$ *and* $\log g$ *from Strömgren photometery*

Observed Strömgren indices may be found in the Hauck & Mermilliod (1990) catalog. They and the corresponding dereddened values are listed in Table 3. For each observation the first row lists the observed indices and the second row lists the dereddened indices. Strömgren indices were dereddened by means of the UVBYBETA code of Moon (1985), as it is more extensively explained in Castelli (1991).

The dereddened indices from Cameron's (1966) observations yield $T_{\rm eff}$=17900 $\pm$ 250 K, $\log g$ = 3.57 $\pm$ 0.02. The Crawford et al. (1970) data are relative to the unresolved double system and therefore the corresponding parameters $T_{\rm eff}$=16440 K and $\log g$ = 4.29 should not be used. All the other β data, when used together with the c index from Cameron (1966), give values for the gravity larger than 4.2. The corresponding effective temperatures are given in parenthesis in Table 3. The E(B-V) values were derived from E(b-y) by means of the Crawford & Mendwewala (1976) relation: E(b-y)/E(B-V)=0.74.

Synthetic c$_0$ indices are from Kurucz (1993a) and synthetic β indices are from Castelli & Kurucz (1994a). They were obtained by normalizing the β indices computed from Kurucz fluxes both on Vega and on the Sun, while the original Kurucz (1993a) β indices were normalized only on Vega.

3.2. $T_{\rm eff}$ *from spectrophotometery*

Breger (1976) lists the spectrophotometric observations from Aller, Faulkner & Norton (1966) after having converted them to the Hayes & Latham (1975) calibration of Vega. In agreement with Hardorp (1966) we found that the Aller et al. data are not fitted shortward of the Balmer discontinuity by any theoretically computed energy distribution, in spite of Aller et al. having corrected their observations for the B component contribution. Hardorp et al. (1968) plotted in their paper the flux distribution of 3 Cen A observed by Rodgers & Hyland (unpublished), both corrected for the contribution of the B8 V component and reduced to the Hayes (1967) calibration of Vega.

We converted the data from the Hardorp et al. (1968) paper to the Hayes & Latham (1975) calibration of Vega and compared the magnitude M$_\nu$=-2.5 log F$_\nu$ normalized at zero at 555.6 nm with the corresponding quantities predicted by Kurucz (1993a) models for different $T_{\rm eff}$ equal to 17500 K, 17750 K, and 18000 K and $\log g$ = 4.3, which roughly approximates the gravity derived from the Stokes (1972) and Strauss & Ducati (1981) β indices. To estimate the reddening E(B-V) from the energy distribution we compared each computed flux with the different observed fluxes corresponding to the reddening corrections for E(B-V) equal to 0.00^m, 0.01^m, and 0.02^m respectively. The conclusion from the visual spectrophotometry is that $T_{\rm eff}$ ranges from 17500 K to 18000 K for E(B-V) included between 0.00^m and 0.02^m (Fig. 1).

3.3. $T_{\rm eff}$ *from the ultraviolet Si lines*

Singh & Castelli (1992) showed that in B-type stars ultraviolet Si III lines of UV mult 4 at 129.4-130.3 nm may be used to fix the silicon abundance and that the Si II lines of the UV multiplet 13.04 at 130.5592, 130.9453, and 130.9725 nm may be used to fix the effective temperature. For 3 Cen A we derived a silicon deficiency of only 0.2 dex from the Si III lines and $T_{\rm eff}$ of about 17500 K from the Si II lines. By comparing observed and

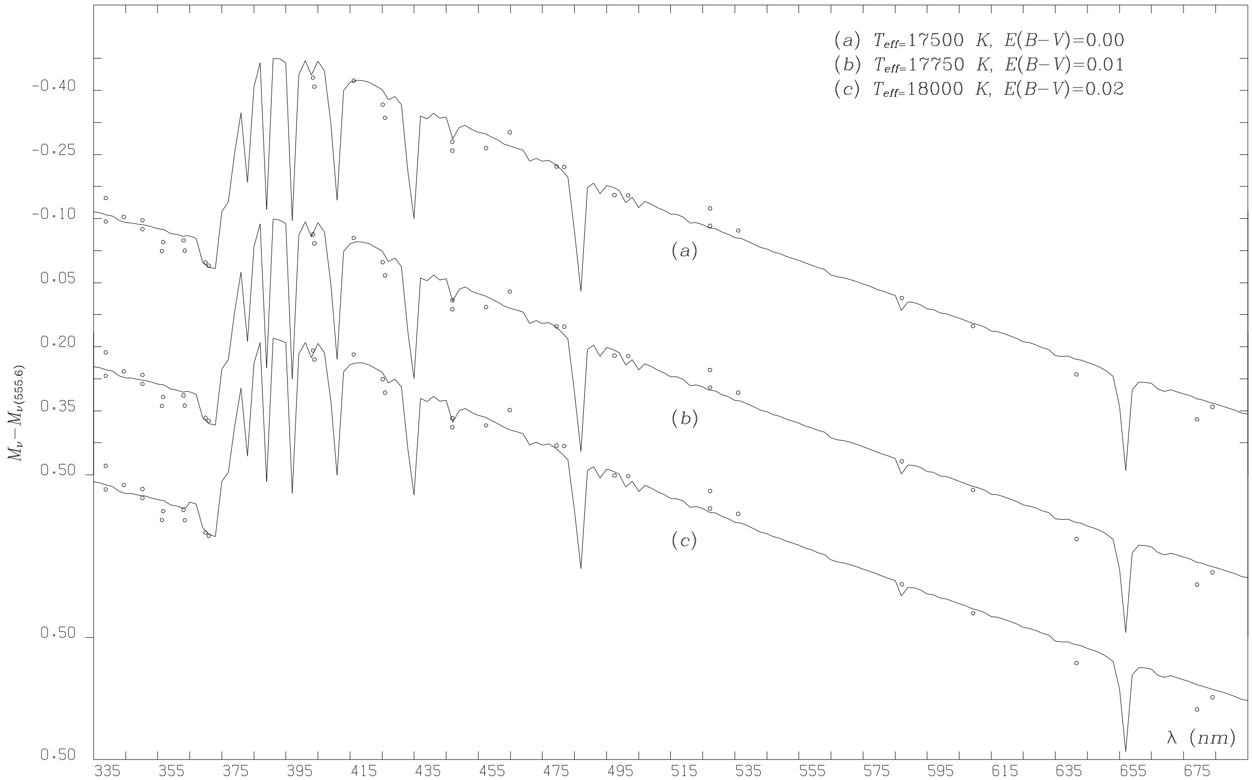

Fig. 1. Comparison, for 3 Cen A, between observed (points) and computed (full lines) energy distributions for different $T_{\rm eff}$ and different E(B-V) values. For all the models log g=4.3 was assumed (a) observations dereddened for E(B-V)=0.00^m are best fitted by $T_{\rm eff}$=17500 K; (b) observations dereddened for E(B-V)=0.01^m are best fitted by $T_{\rm eff}$=17750 K; (c) observations dereddened for E(B-V)=0.02^m are best fitted by $T_{\rm eff}$=18000 K;

computed spectra we found that the larger temperature 17900 K derived from the Cameron (1966) photometry yields too weak UV Si II profiles and too strong UV Si IV profiles.

3.4. log *g from Balmer profiles*

We compared the Hγ profile tabulated in Sargent & Jugaku (1961) and the Hγ and Hδ profiles tabulated in Norris (1971) with profiles computed with models with different $\log g$ and $T_{\rm eff}$=17500 K, as derived from the UV Si II profiles. The H_γ profile from Sargent & Jugaku (1961) is fitted by $\log g$ = 3.7 and the profiles from Norris (1971) are fitted by $\log g$ = 3.8 (Fig. 2).

3.5. *The microturbulent velocity*

We did not find any way to estimate the microturbulent velocity from the ultraviolet region owing to the large blanketing, which does not permit to measure equivalent widths of strong and weak unblended lines, and to the large noise. Hardrop et al. (1968) found that the microturbulent velocity of 3 Cen A is included between 0 and 2 km s^{-1}. We assumed 0 km s^{-1} for computing spectra.

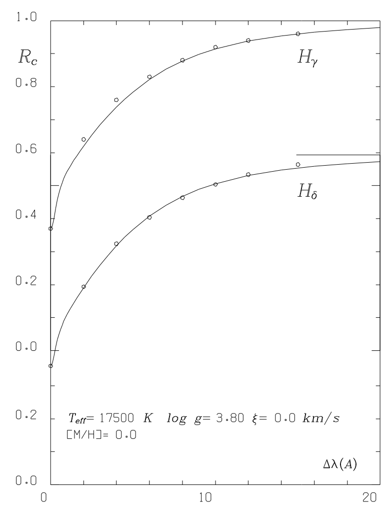

Fig. 2. Comparison, for 3 Cen A, between observed H_γ and H_δ profiles from Norris (1971) (points) and computed profiles (full lines) for a model with $T_{\rm eff}$=17500 K and log g=3.80

3.6. *Adopted model parameters*

The comparison between photometric, spectrophotometric, and spectroscopic observations with the corresponding computed

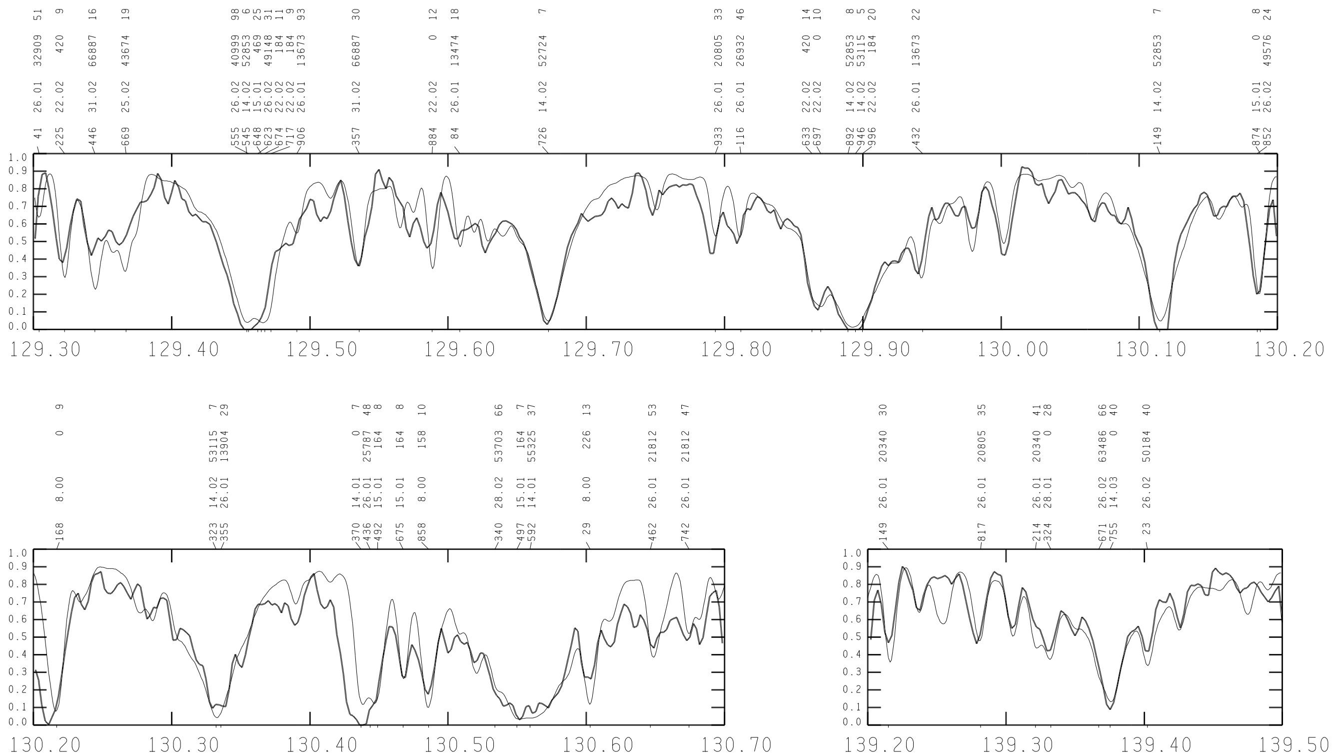

Fig. 3. Comparison, for 3 Cen A, between observed (thick line) and computed (thin line) Si II, Si III, and Si IV profiles. Model parameters are $T_{\rm eff}$=17500 K, log g=3.80, ξ=0 km s^{-1}

quantities has shown that $T_{\rm eff}$ and log g have values included in the range 17500-18000 K and 3.5-4.5 dex, respectively. Because the main purpose of this paper is the analysis of spectroscopic data we have given more weight to the values derived from the high-resolution observations, which are also unaffected by possible contamination due to the B8 V component and to the reddening.

The ATLAS9 model atmosphere used in this paper for computing spectra and deriving abundances has parameters $T_{\rm eff}$=17500 K, log g = 3.8, solar abundances, and zero microturbulent velocity. This model fits the visual energy distribution for E(B-V)=0.00, well reproduces the Hγ and Hδ profiles observed by Norris (1971), and provides computed ultraviolet Si II, Si III, and Si IV profiles which agree rather well with the observed ones. Fig. 3 compares observed Si II, Si III, and Si IV profiles with the profiles predicted by the adopted model and a silicon underabundance of 0.2 dex. Table 4 compares the parameters adopted in this paper with those given in the literature.

Table 4. $T_{\rm eff}$ and log g for 3 Cen A from the literature

$T_{\rm eff}$ (K)	log g	method	models	sources
17500	3.80	UV Si lines, Hγ	K93	this paper
19500	4.0	c$_o$,β indices	M1	HW
18500	4.2	c$_o$,β indices	K79	HW
19350	3.87	Si II/Si III;Hγ	H66	HBP
19197	4.18	Walraven photometry	K79	GZL
18200	3.7		H66	TSJ
19100	3.9	Geneva phot. and HBP		STK
18327	4.0	Flux distrib. and Balmer lines	BM	N
17500	4.25	UV Si lines,β index	K89	SC
18700	4.20	Geneva photometry, β index	LGK	LADM

Models:
M1: Mihalas(1972);K79: Kurucz(1979);H66: Hardorp(1966)
BM: Bradley & Morton; K89: Kurucz(1989)
LGK: Lester et al.(1986);K93: Kurucz(1993a)

Sources:
HW: Heasley & Wolff (1983); HBP: Hardorp et al. (1968)
GZL: de Geus et al.(1989);STK: Sadakane et al. (1983)
N: Norris(1971);SC: Singh& Castelli(1992);
LADM: Lanz et al. (1993);TSJ: Takada-Hidai et al. (1986)

4. The atmospheric parameters of the comparison stars ι Her and Feige 86

4.1. ι Her

Castelli & Bonifacio (1990) derived $T_{\rm eff}$=17180 K, log g = 3.43 for ι Her. These parameters were obtained by comparing the observed Strömgren indices c and β with the synthetic indices of the Lester, Gray, & Kurucz (1986) grid. We revised these parameters by using the new synthetic c and β indices described in Sect. 3.1. We obtained $T_{\rm eff}$=17100$\pm$250 K, log g = 3.80$\pm$0.02, E(B-V)=0.03. These atmospheric parame-

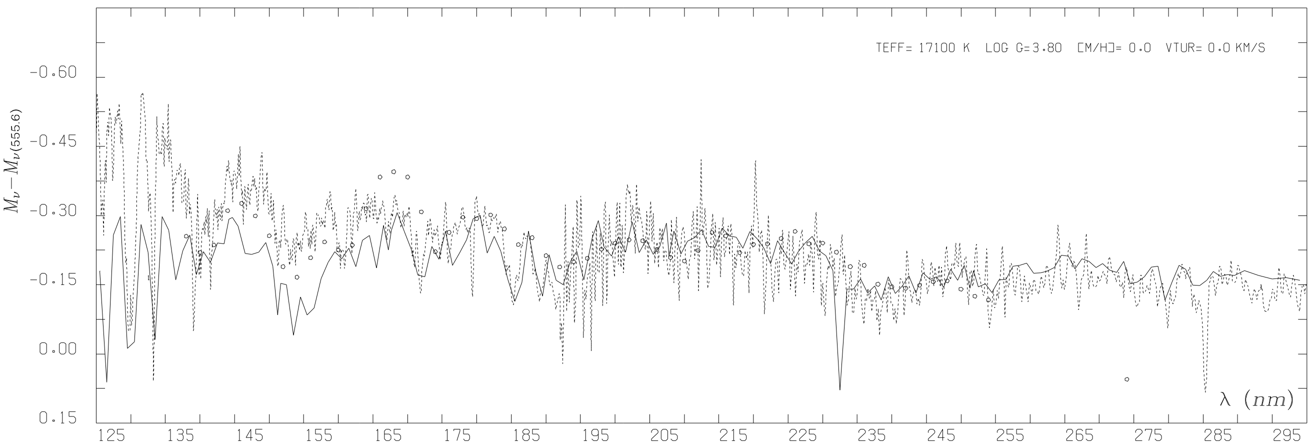

Fig. 4. Comparison, for ι Her, between observed and computed energy distributions. Observations are from S2/68 TD1 experiment (points) and from IUE (dashed line) images. Computed magnitudines (normalized to zero at 555.6 nm) (full lines) are for $T_{\rm eff}$=17100 K, log g = 3.8, ξ=0 km s^{-1}. Observations have been dereddened for E(B-V)=0.02^m

ters are weakly dependent on E(B-V). In fact, for E(B-V)=0.00, the parameters become $T_{\rm eff}$=17020±250 K, log g = 3.77±0.02. The errors are those related with the fitting procedure.

By assuming log g=3.80, the spectrophotometric observations from the KUB, JUS, and KO sources listed in Breger's (1976) catalog are fitted by $T_{\rm eff}$=16750 K and E(B-V)=0.00, by $T_{\rm eff}$=16500 K and E(B-V)=0.01, and by $T_{\rm eff}$=17100 K and E(B-V)=0.00, respectively. No single model is able to fit the data from WKH source, also given in the catalog.

We adopted as final parameters for ι Her $T_{\rm eff}$=17100 K and log g=3.80, as derived from the Strömgren photometry, mostly because they are nearly independent of the reddening. Also for ι Her, as for 3 Cen A, we adopted ξ=0 km s^{-1}.

This model fits very well the flux from the IUE low resolution images SWP42454L and LWP21228L for $\lambda > 180$ nm, provided that E(B-V)=0.02 is assumed. However, the region for λ<180 nm requires either $T_{\rm eff}$ larger than 17100 K for E(B-V)=0.02 or E(B-V)=0.0 for $T_{\rm eff}$=17100 K (Fig 4). This discrepancy may be due either to problems related with the IUE flux calibration or to some too large computed blanketing for the B-type stars in the far ultraviolet, which could be due to the several Fe III lines arising from predicted levels. The IUE flux agrees very well with that observed by the S2/68 TD1 instrument (Jamar et al.,1976).

The comparison of the observed and computed Balmer profiles confirms the value log g = 3.8 derived from the β index (Bonifacio, 1994).

4.2. Feige 86

The model parameters for Feige 86 were derived from the Strömgren photometry. They are $T_{\rm eff}$=16430 ± 250 K and log g = 4.2 ± 0.02. We checked them with the visual energy distribution and the Balmer profiles. The interstellar reddening was estimated to be E(B-V)=0.075. Also for this star we assumed ξ=0 km s^{-1}. More details are given in Bonifacio et al. (1995).

5. The analysis

Abundances were estimated by comparing observed and computed spectra. The errors affecting the resulting abundances may be very large, mostly for elements with few either observed or computed lines. Weak lines give uncertain abundances owing to the very low S/N ratio of the IUE spectra, while the strongest resonance lines are poorly computed owing to the LTE approximation. Also possible interstellar contributions may modify the stellar profile.

Spectra were computed by using the SYNTHE code (Kurucz,1993b) and the Kurucz (1993b) line lists modified in the 120-200 nm region as described in Castelli & Bonifacio (1990). Also in the 200-330 nm region lines of the iron group in Kurucz line lists were replaced by those from Fuhr, Martin & Wiese (1988) and Martin, Fuhr & Wiese (1988) when available. Only for Sc II the Kurucz lines were preferred, because those of Martin et al. were taken from the previous Kurucz & Peytremann (1975) computations. Furthermore we added lines of Ga II and Ga III (Castelli & Parthasarathy, 1995), Au II (Wyart,1996) and Au III (Wyart et al., 1996), Pt I (Whalgren et al.,1995), Pt II (Wyart et al., 1995), and Pt III (Ryabtsev et al., 1993).

To take into account the instrumental effects the computed spectra were broadened by means of a gaussian function with FWHM corresponding to the IUE nominal resolutions listed in Table 2. Because for the long-wavelength region this broadening yielded too broad lines, we preferred to adopt an instrumental resolution of 15 km s^{-1} for all the three stars. Furthermore, for 3 Cen A, we found that it was not necessary to add any further broadening to reproduce the width of the observed profiles, so that we assumed v*sini*=0 km s^{-1}. Zero rotational velocity for 3 Cen A was also adopted by Norris (1971). The computed spectra of ι Her and Feige 86 were both broadened for v*sini*=11 km s^{-1}.

The analysis of the ultraviolet spectra was performed by comparing two different single images rather than to analyze the only one image resulting from the coaddition of several spectra. Some tests based on our images have shown that this last method, even if improves the signal to noise ratio, does not still permit to discriminate between the noise and real features. In the IUE coadded spectrum the noise still affects the image as in the single spectra so that the use of only one coadded image hampers any knowledge of the position and size of the noise. We assumed that observed features are reliable when they coincide in wavelength and intensity in two different spectra.

To point out the similarities and the differences of the three stars we compared the observed spectra each with the other and the observed spectra with the synthetic spectra. This comparison was performed by superimposing each time two different spectra normalized to the continuum level. For each star two observed spectra were compared each with the other, except for Feige 86 in the 200-300 nm region, because only one IUE image was available to us for this star in this range. We produced an ultraviolet Atlas of ι Her, 3 Cen A, and Feige 86 (Castelli et al., 1995).

The ultraviolet spectrum of 3 Cen A is very similar to that of ι Her, except for the much weaker B I line at 136 nm and for the much stronger lines of phosphorus and gallium. Very striking features in 3 Cen A are the resonance lines of Ga II at 141.444 nm and of Ga III at 149.5045 nm and 153.4462 nm, which are very broad. After having fixed the abundances of the observed elements, the quality of the agreement between the observed and computed spectra is very similar to that obtained for ι Her, so that the spectrum of this peculiar star can be predicted fairly well.

On the contrary, there are several differences between the ultraviolet spectra of 3 Cen A and Feige 86 which cannot be eliminated by simply modifying the abundance, so that the assumption of the similarity of the two stars is not so strightforward as it was always assumed.

6. Abundances of 3 Cen A

6.1. Helium

The most striking peculiarity of 3 Cen A is its helium deficiency combined with the large ^{3}He/^{4}He isotopic ratio equal to 2.5 (Hartoog & Cowley, 1979). The meteoritic value is 1.42 10^{-4} (Anders & Grevesse ,1989). The helium abundance log (N_{He}/N_H)=-1.84 derived by Hardorp et al. (1968) corresponds to a helium deficiency of 0.83 dex, if the solar ratio log (N_{He}/N_H)=-1.01 from Anders & Grevesse (1989) is assumed.

We estimated the LTE helium abundance yielded by the model adopted in this paper by comparing the observed He I profiles at 438.79 nm and 447.15 nm plotted by Jugaku, Sargent, & Greenstein (1961) with profiles computed by us with different abundances. The best fit is obtained by assuming a helium abundance log $(N_{He}/N_H) = -1.56$, corresponding to a He deficiency of 0.55 dex. We computed profiles both for an isotopic ratio ^{3}He/^{4}He=2.5 and for the only ^{4}He. The only perceptible difference between the two profiles is that they are shifted each from the other as consequence of the isotopic shifts for pure ^{3}He assumed to be 0.028 nm for the 438.79 nm and 0.007 nm for λ 447.15 nm (Hartoog & Cowley ,1979).

We compared the He I profiles of 3 Cen A with those of Feige 86. Fig. 5, upper plot, is the comparison between the observed He I profiles of Feige 86 (thin line) and the oserved He I profiles of 3 Cen A (thick line). The larger He abundance in 3 Cen A is evident. The middle plot compares the observed (thick lines) and computed (thin lines) profiles in Feige 86. For both He I lines at 438.79 nm and 447.15 nm the computed core is stronger than the observed one. We were not able to find any ATLAS9 model which fits the He I lines in Feige 86, also by changing the He abundance. The lower plot of Fig. 5 compares observed (thick lines) and computed (thin lines) profiles of 3 Cen A. The agreement is much better than that for Feige 86. However, we assumed two different resolwing powers for the synthetic spectra in the 438.8 nm and 447.1 nm regions without knowing if they agree with the resolwing power of the spectra used by Jugaku et al. (1961). We assumed $\lambda/\Delta\lambda$=5000 at λ=438.8 nm and $\lambda/\Delta\lambda$=8500 at λ=447.1 nm. Details on the computations of the He I line profiles may be found in Bonifacio et al. (1995).

6.2. Abundances from the ultraviolet region

Abundances were estimated from the 122.8-195.0 nm region by analyzing the lines listed in Tables V and VI in Castelli & Bonifacio (1990) and the lines discussed by Bonifacio et al. (1995) for each ion identified in Feige 86. We excluded the “peculiar lines” listed in Bonifacio et al. (1995).

The abundances derived from the 122.8-195.0 nm region were then used for computing synthetic spectra for the 200-300 nm region, which is crowded mostly with lines of Cr II, Cr III, Mn II, Mn III, Fe II, Fe III, Ni II, and Ni III. Among the other elements, only lines of Mg II at 279.5, 280.2, 293.6, 292.8, 279.7, 279.0 nm, and the resonance lines of Zn II at 202.5 and 206.2 nm yield an appreciable contribution to the line absorptions.

The agreement between the observed and computed features appears much worse in the long-wavelength region than in the short one, in the sense that the computed spectrum is generally weaker than the observed spectrum. Furthemore, the IUE spectra are affected by a such large noise between 200.0 and 240.0 nm that they may be used in this range only for identification purposes. However, this behaviour is the same also in the case of ι Her and Feige 86, so that we have assumed that it should be related with the reduction of the IUE spectra in the long-wavelength region rather than with large errors in abundance determinations.

The most important result from the analysis of the 200-300 nm region is the occurrence of some lines so much stronger than those computed with the selected abundances that this dis-

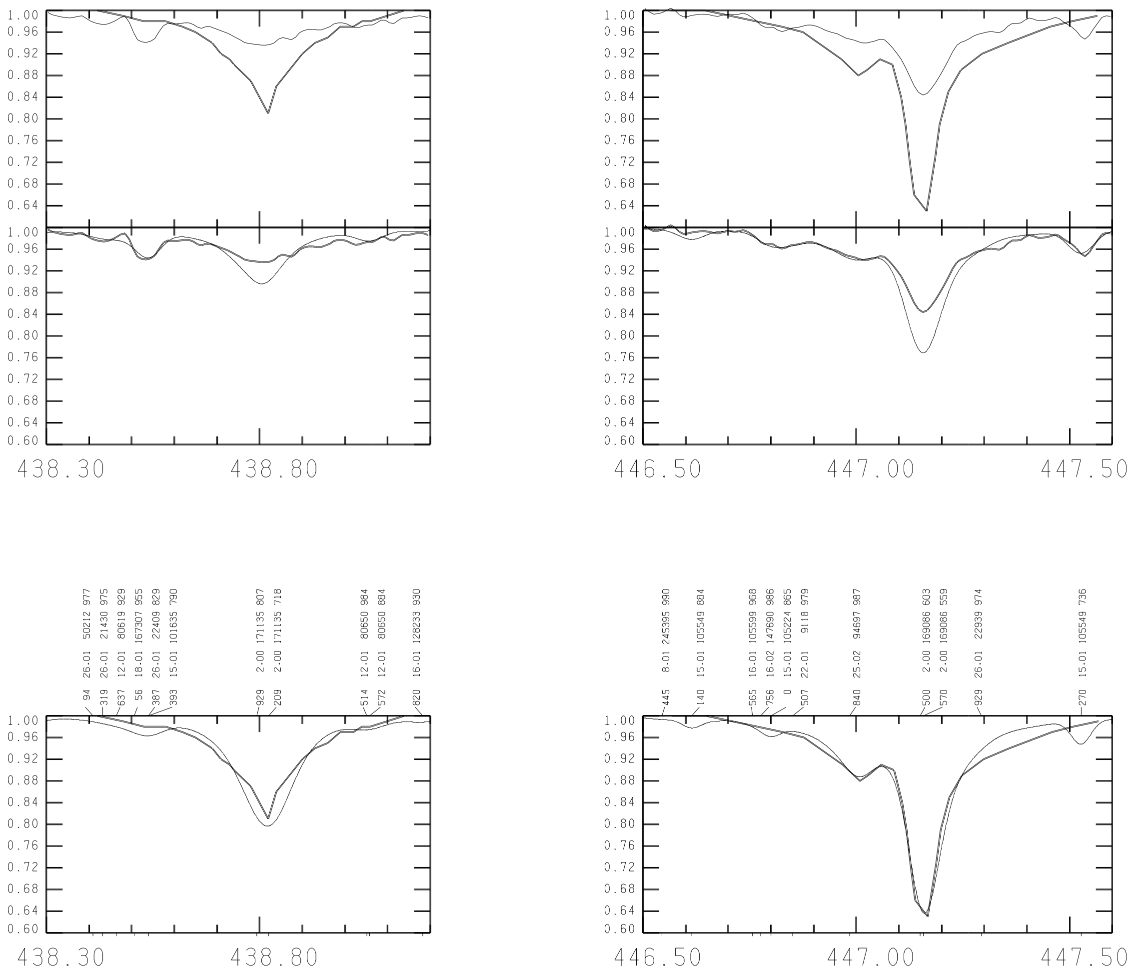

Fig. 5. Comparison between observed and computed He I profiles of 3 Cen A and Feige 86. From top to bottom: observed He I profiles of 3 Cen A (thick lines) are compared with observed He I profiles of Feige 86 (thin lines); observed He I profiles of Feige 86 (thick lines) are compared with profiles computed from a model with $T_{\rm eff}$=16430 K, log g=4.2, ξ=0 km s^{-1} (thin lines); observed He I profiles of 3 Cen A (thick lines) are compared with profiles computed from a model with $T_{\rm eff}$=17500 K, log g = 3.8, ξ=0 km s^{-1} (thin lines)

agreement has to be considered real and not caused only by the poor quality of the IUE data and by the uncertainties in the atomic data and line lists used for computing synthetic spectra. For most of these lines, the lower level is the ground level. If these lines were used for fixing abundances, they would yield abundances much larger than those derived from the other lines of the spectrum. Strong lines are discussed in Sec. 9.

The comparison of the IUE spectrum of 3 Cen A with a synthetic spectrum has given the following estimates for the abundances: Al [-1.5] is the most underabundant element, followed by B [-1.0], C [-0.75], He [-0.55], N [-0.5], and Mg [-0.5]. Also Ca is probably underabundant ([-1.0]). The most overabundant element is Hg [+4.5], followed by Kr [+3.3], Ga [+3.25], Cu [+2.0], P [+1.6], Mn [+1.4], Sc [+1.0]. The other elements have solar or almost solar abundances. Table 5, column 2, summarizes the abundances of 3 Cen A used by us for computing the UV spectrum and compares them with values taken from the literature. Optical abundances listed in column 3 are from Hardorp et al. (1968). Furthermore, we listed the abundances of Al and Ga derived by Sadakane et al. (1983), Takada-Hidai et al. (1986), and Lanz et al. (1993). Sadakane et al. (1983) and Takada-Hidai et al. (1986) measured the equivalent widths of the Al II, Al III, Ga II, and Ga III resonance lines on HR IUE spectra. Lanz et al. (1993) used red spectra to fix the Ga abundance and they found a 0.3 dex larger value than that obtained by Takada-Hidai et al. (1986). Column 6 in Table 5 lists solar abundances log ϵ=log(N_{elem}/N_{tot}) taken from Anders & Grevesse (1989), except for iron for which the abundance from Hannaford et al. (1992) was assumed. Abundances are on the scale of total atomic number. On this scale, the solar hydrogen and helium abundances N_H/N_{tot} and N_{He}/N_{tot} are 0.911 and 0.089 respectively.

The analysis of the ultraviolet spectrum has permitted us to estimate the abundances of B, Al, Sc, Cu, and Hg, which are not observable in the optical region. Fig. 6a shows the metallicity of 3 Cen A relative to the solar one and compares available abundances derived from the optical region (dark points) with those we obtained from the UV spectra (open circles). The largest

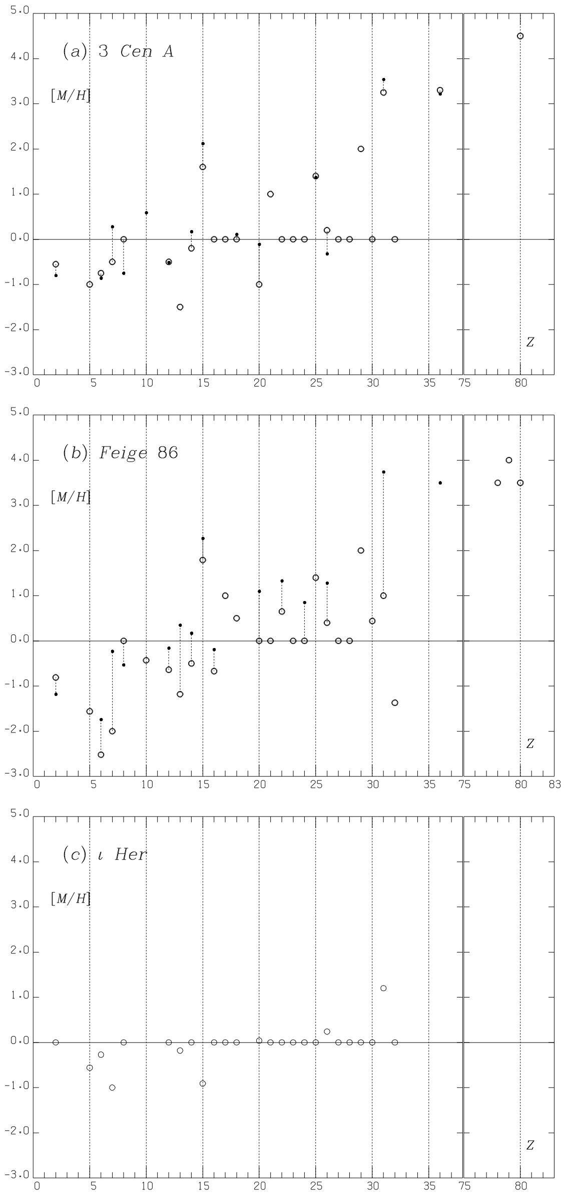

Fig. 6a–c. The abundance patterns of **a** 3 Cen A; **b** Feige 86; **c** ι Her; the open circles are the abundances relative to the Sun derived in this paper, the dark points are abundances relative to the Sun from visible data from the literature

differences occur for N, O, and Ca. However, the discrepancy for Ca may be not real, owing to the uncertainty of our determination.

7. The abundances of the comparison stars Feige 86 and ι Her

7.1. Feige 86

The abundances of Feige 86 are those listed in Bonifacio et al. (1995), except for Mn, whose abundance $\log(N_{Mn}/N_{tot})$ was increased from -5.96 dex up to -5.25 dex on the basis of the analysis of the 200-300 nm region. The solar value is -6.65 dex. Furthermore, computations of synthetic spectra with different As abundances lead us to conclude that any reliable value cannot be fixed for this element from our data. Finally, we assumed for As solar abundance instead of an overabundance of 2 dex as in Bonifacio et al. (1995).

We also further investigated the Pt and Au spectra in Feige 86 on the basis of the much more extended line lists which became available to us after the Bonifacio et al. (1995) paper.

None of the Pt I lines listed in Whalgren et al. (1995) are predicted or observed in the spectrum, but all the Pt II and Pt III lines with available $\log gf$ (Wyart et al.,1995; Ryabtsev et al., 1993) are predicted and very often they very well match features observed in Feige 86, and not present in 3 Cen A. Usually the predicted lines are part of blended features. This fact and the large noise of the spectra did not permit us to fix an exact value for the Pt abundance but there is no doubt that Pt is present in Feige 86 with an overabundance not lower than 3.5 dex.

Also all the Au II and Au III lines with available $\log gf$ (Wyart, 1996; Wyart et al., 1996) are predicted and observed. As for Pt, they are mostly blended features. By assuming an overabundance of 4 dex for gold, the predicted lines are sometimes stronger than the observed ones, but in other cases they are weaker. Therefore the adopted abundance may be considered an average value affected by an uncertainty on the order of 1 dex.

Fig. 6b compares the abundances of Feige 86 derived by Baschek & Sargent (1976) from the optical region (dark points) with those listed in column 4 of Table 5 (open circles). Most of the abundances from Table 5 are lower than those derived by Baschek & Sargent (1976), in particular the Ga abundance. However, Baschek & Sargent (1976) gave only upper limits for all the abundances, except for He, Si, P, and Fe. Therefore, Bonifacio et al. (1995) not only increased the number of elements for which the abundances were determined, but they also better estimated the abundance for nearly all the observed elements.

The improvement of the agreement between the observed and computed spectra of Feige 86 when the Pt II, Pt III, Au II, and Au III lines have been added in the line lists strengthens the hypothesis that several heavy elements are overabundant in this star (Castelli et al., 1995). For this reason, the line spectrum cannot be easily predicted. In fact, the atomic data of the heavy elements are poorly known, in particular when they are in the ionized states.

7.2. ι Her

The slightly different model parameters and the use of a Kurucz ATLAS9 model computed with microturbulent velocity ξ=0 km s^{-1} instead of an ATLAS8 model with ξ=2 km s^{-1}, did not modify in an appreciable way the computed spectra, so that we kept the abundances given by Castelli & Bonifacio (1990). The abundances relative to the solar ones are listed in Table 5, column 5 and are plotted in Fig. 6c.

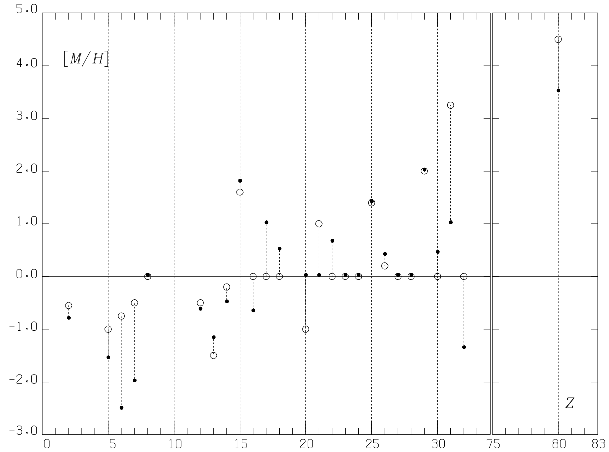

Fig. 7. The comparison between the abundance pattern of 3 Cen A (o) and that of Feige 86 (dark points)

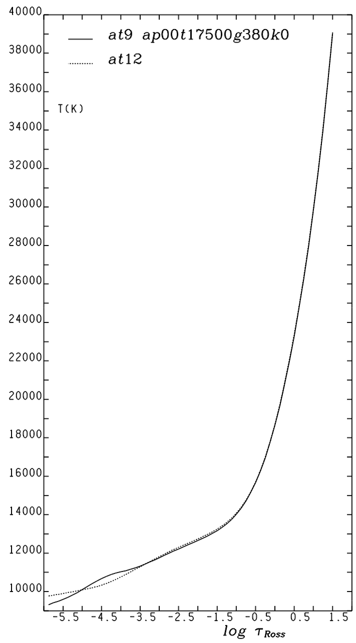

Fig. 8. The T-log τ_{ross} relations from ATLAS9 and ATLAS12 models

Table 5. Abundances of 3 Cen A, Feige 86, and ι Her relative to the solar abundances $\log(N_{elem}/N_{tot})$

(1) Elem	(2) 3 Cen A UV	(3) 3 Cen A visible	(4) Feige 86	(5) ι Her	(6) Sun
He	[−0.55]	[−0.83]	[−0.81]	[0.00]	−1.05
B	[−1.00]		[−1.56]	[−0.56]	−9.44
C	[−0.75]	[−0.89][1]	[−2.52]	[−0.27]	−3.48
N	[−0.50]	[+0.25][1]	[−2.00]	[−1.00]	−3.99
O	[0.00]	[−0.78][1]	[0.00]	[0.00]	−3.11
Ne		[+0.56][1]	[−0.43]		−3.95
Mg	[−0.50]	[−0.54][1]	[−0.64]	[0.00]	−4.96
Al	[−1.50]		[−1.18]	[0.00]	−5.57
	[−0.97][2]				
Si	[−0.20]	[+0.14][1]	[−0.50]	[−0.21]	−4.49
P	[+1.60]	[+2.09][1]	[+1.79]	[−0.90]	−6.59
S	[0.00]		[−0.67]	[0.00]	−4.83
Cl	[0.00]		[+1.00]	[0.00]	−6.54
Ar	[0.00]	[+0.08][1]	[+0.50]	[0.00]	−5.48
Ca	[−1.00]?	[−0.14][1]	[0.00]	[0.00]	−5.68
Sc	[+1.00]		[0.00]	[0.00]	−8.94
Ti	[0.00]		[+0.65]	[0.00]	−7.05
V	[0.00]		[0.00]	[0.00]	−8.04
Cr	[0.00]		[0.00]	[0.00]	−6.37
Mn	[+1.40]	[+1.34][1]	[+1.40]	[0.00]	−6.65
Fe	[+0.20]	[−0.35][1]	[+0.40]	[+0.20]	−4.56[5]
Co	[0.00]		[0.00]	[0.00]	−7.12
Ni	[0.00]		[0.00]	[0.00]	−5.79
Cu	[+2.00]		[+2.00]	[0.00]	−7.83
Zn	[0.00]		[+0.44]	[0.00]	−7.44
Ga	[+3.25]	[+3.51][1]	[+1.00]	[+1.20]	−9.16
	[+3.12][3]				
		[+3.72][4]			
Ge	[0.00]		[−1.37]	[0.00]	−8.63
As	[0.00]		[0.00]?	[0.00]	−9.67
Kr	[+3.3]	[+3.19][1]		[0.00]	−8.81
Mo			>>[0.00]		−10.12
Ru			[0.00]?		−10.20
Rh			>[0.00]?		−10.92
In			[+1.6]		−10.38
Pt			[+3.5]		−10.24
Au			[+4.0]		−11.03
Hg	[+4.5]		[+3.5]		−10.95
Bi			[+5.0]?		−11.33

[1] Hardorp et al.(1968); [2] Sadakane et al.(1983)
[3] Takada-Hidai et al.(1986); [4] Lanz al.(1993)
[5] Hannaford et al.(1992)

8. Comparison of abundances

Fig. 7 directly compares the abundances of 3 Cen A (open circles) with those of Feige 86 (dark points). The largest difference is yielded by Ga, which is more than 100 times more abundant in 3 Cen A than in Feige 86. The light elements B, N, and C are more underabundant in Feige 86 than in 3 Cen A. Furthermore, lines of Pt II, Pt III, Au II, Au III, (and probably also of Mo III and Rh II) can be identified in Feige 86, but not in 3 Cen A.

9. The strong ultraviolet lines

In all the three stars there are some lines much stronger than the computed ones. The lines yielding the most conspicuous discrepancy are listed in Table 6. Only NLTE computations may help to clarify whether they are ill-predicted lines by LTE computations or they are a blend of stellar and interstellar components. The small radial velocity of the stars and the rather low resolution of the IUE spectra do not permit to separate the stellar lines from eventual interstellar components. The radial velocities (relative to the Sun) are -20 km s^{-1} for ι Her (Lesh, 1968), 14 km s^{-1} for 3 Cen A (Hoffleit & Warren Jr., 1994),

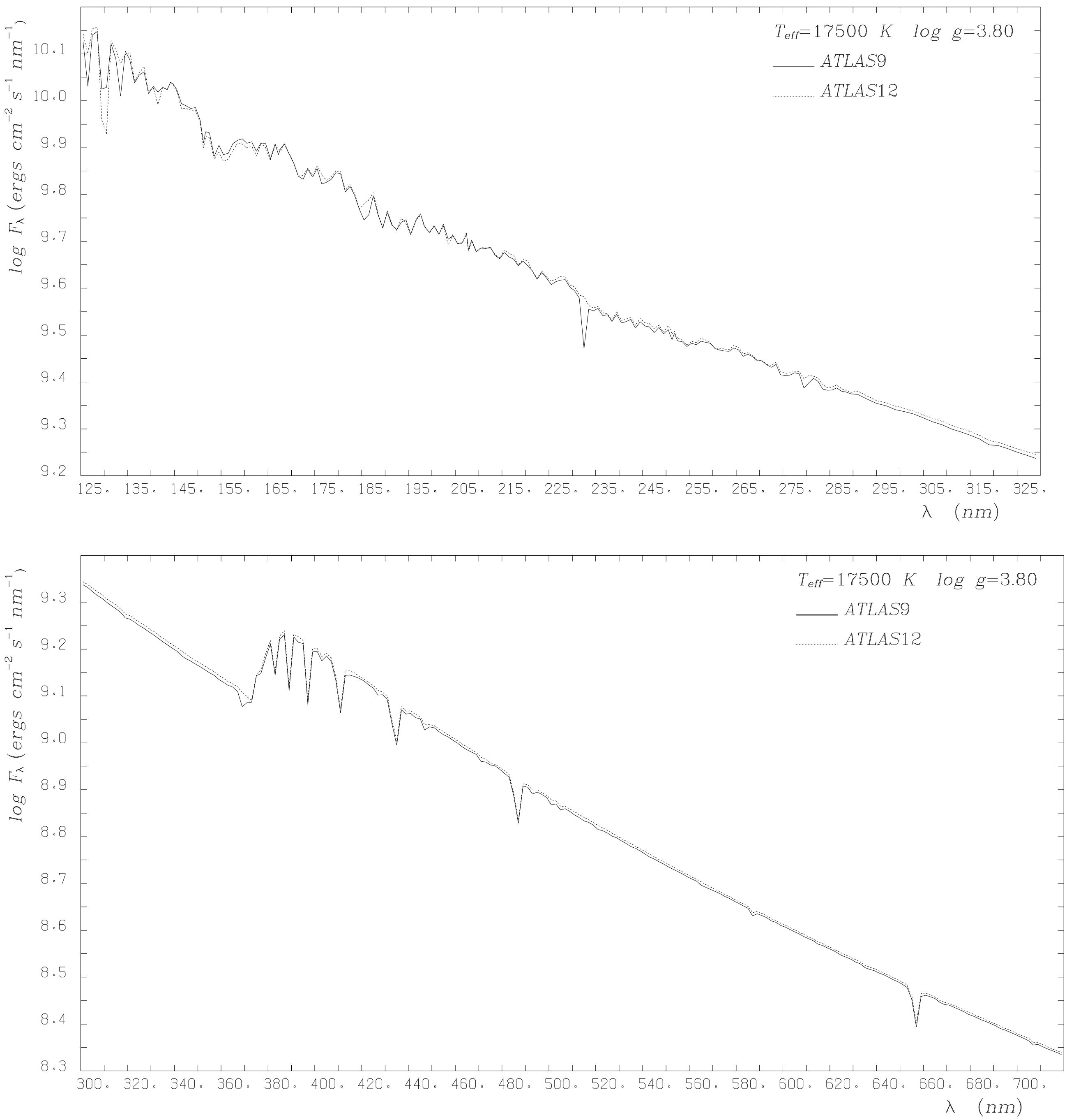

Fig. 9. Comparison of energy distributions computed from the ATLAS9 and ATLAS12 models having the same parameters $T_{\rm eff}$=17500 K, log g=3.8, but different abundances. Solar abundances were used in ATLAS9, abundances of 3 Cen A in ATLAS12

and -23 km s^{-1} for Feige 86 (Berger, 1963). Abundances from the lines listed in Table 6 are usually not consistent with the abundances derived from the other lines of the spectrum. Table 7 shows the abundances derived from the resonance lines of Mn II and compare them with the abundances derived from the other Mn II and Mn III lines and adopted for computing the whole synthetic spectrum.

10. The opacity-sampled model

The abundances of 3 Cen A listed in column 2 of Table 5 were used to compute an opacity sampled ATLAS12 model having the same parameters $T_{\rm eff}$=17500 K, and log g = 3.8 of the ATLAS9 model. More details on the ATLAS12 code may be found in Kurucz (1993c, 1996) and in Castelli & Kurucz (1994b). Fig. 8 shows that the T-log τ_{ross} relations from the ATLAS9 and ATLAS12 codes are somewhat different only in the layers for which $\log(\tau_{Ross}) < -3.5$. Fig. 9 shows that starting from about 225.0 nm the flux computed from the ATLAS12 model is larger of about 1.5 % than that computed from the ATLAS9 model. The difference decreases toward the red and it is on the order of 0.7 % longward H_α. The most remarkable differences are due to differences in the line lists. In fact, the line lists used for computing the synthetic spectrum are a later version of those used for the ODF computations. The energy distribution corresponding to the ATLAS12 model was computed by degrading a synthetic spectrum to the resolution of the ATLAS9 opacity distribution functions.

The conclusion is that in the case of 3 Cen A, the model structure does not change in an appreciable way when the specific abundances of the peculiar star are used for computing the model.

11. Conclusions

The ultraviolet spectrum of the ^{3}He Pop I Bp star 3 Cen A, belonging to the P-Ga subgroup, is very similar to that of the normal star ι Her, in the sense that the same features can be observed in both stars, although some of them have different intensities, owing to the some different elemental abundances. On the contrary, the ultraviolet spectrum of 3 Cen A is rather different from that of the ^{3}He Pop II horizontal-branch Bp star Feige 86. The different behaviour of the spectra is mostly due both to the presence in Feige 86 of numerous lines of heavy elements (Pt II, Pt III, Au II, Au III, and possibly Mo III) not observed in 3 Cen A and to the larger underabundance in Feige 86 than in 3 Cen A of C and N. Another striking difference between 3 Cen A and Feige 86 is yielded by helium. In spite of both stars being He-weak, the He I lines can be well reproduced by the computations in 3 Cen A but not in Feige 86 (Fig. 5). Also Ga is about 2 dex more abundant in 3 Cen A than in Feige 86.

Because P-Ga subgroup of the He-w early Bp stars may be considered as a hot continuation of the Hg-Mn stars, we have compared the abundances of both 3 Cen A and Feige 86 with those of the Mn-Hg stars. Smith & Dworetsky (1993) discussed the abundances of Mn, Fe, Co, Ni as derived from the IUE spectra. They find a correlation of the Mn abundance with $T_{\rm eff}$, and showed that the Mn abundance increases for $T_{\rm eff}$ increasing from 11000 K to 15000 K. Only seven Hg-Mn stars out of the 26 stars of their sample lie below the relation. 3 Cen A and Feige 86 should be added to these seven stars if the Mn abundance is derived from the general agreement between the observed and computed Mn lines; on the contrary, the Mn abundance of both 3 Cen A and Feige 86 has to be increased up to 100 times if the only three Mn II lines at $\lambda\lambda$ 257.6, 259.3, 260.5 nm are used to fix the Mn abundances, as was done by Smith & Dworetsky (1993). Smith & Dworetsky (1993) showed that most of the Hg-Mn stars of their sample have Co and Ni underabundant, while the abundance of Cr and Fe lie around the solar values. For none of these elements did they find a clear correlation between abundance and $T_{\rm eff}$. For both 3 Cen A and Feige 86 the abundances of Cr, Co and Ni are about solar, as for the Hg-Mn stars. The Fe abundance is enhanced of about 0.2 dex in 3 Cen A and 0.4 dex in Feige 86 if the solar iron abundance is $\log N_{Fe}/N_{tot} = -4.56$ (Hannaford et al., 1992).

Table 6. Lines which require a NLTE analysis and which may also be affected by interstellar components

Elem.	mult	λ nm	χ_{exc} cm^{-1}
C I	2	165.6929	0.0
	3	156.0309	0.0
	4	132.8834	0.0
	5	128.0135	0.0
	7	127.7282	0.0
	9	126.0735	0.0
C II	1	133.4532	0.0
	1	133.5563	63.0
	1	133.5708	63.0
O I	2	130.2168	0.0
Mg I	1	285.2126	0.0
Mg II	1	280.2705	0.0
	1	279.5528	0.0
		123.9925	0.0
Al II	2	167.0787	0.0
Al III	1	186.279	0.0
Si I	1	251.4316	0.0
Si II	1	180.8013	0.0
	2	152.6707	0.0
	3	130.437	0.0
	4	126.042	0.0
S I	1	180.7311	0.0
S II	1	125.9519	0.0
	1	125.3811	0.0
	1	125.0584	0.0
Mn II	1	260.5684	0.0
	1	259.3724	0.0
	1	257.6105	0.0
Fe II	1	259.9396	0.0
	1	258.5876	0.0
	2	238.2039	0.0
	2	237.3736	0.0
	3	234.3496	0.0
	8	160.8451	0.0
Zn II	1	206.2662	0.0
Ga III	1	149.5045	0.0

For the same sample of Hg-Mn stars studied by Smith & Dworetsky, Smith (1993) found that the Si abundance lies around the solar value, while for most of the stars Mg and Al are underabundant. Also for these elements he did not find a clear correlation between abundance and $T_{\rm eff}$. In both 3 Cen A and Feige 86 the Si, Mg, and Al abundances are included within the abundance limits of the Hg-Mn stars studied by Smith (1993), but the Mg abundance lie at the lower limit.

In a successive paper Smith (1994) analyzed the Cu and Zn abundances in the same sample of Hg-Mn stars and he found that Zn is underabundant in most stars without any correlation with $T_{\rm eff}$, while Cu is generally overabundant and the Cu overabundance seems to increase with increasing temperature. Zn

Table 7. LTE Mn abundances from the lines of Mn II UV mult. 1 compared with the abundances derived from other Mn II and Mn III UV lines

λ(nm)	χ_{exc}	$\log(N_{Mn}/N_{tot})$ 3 Cen A	Feige 86	ι Her
260.5684	0.0	-4.25	-4.75	-5.65
259.3724	0.0	-4.25*	-4.75*	-5.65*
257.6105	0.0	-3.50	-5.50	-5.65
other lines		-5.25	-5.25	-6.65

* blend

was found solar in 3 Cen A and overabundant less than 0.5 dex in Feige 86, while Cu was found overabundant by 2 dex in both stars. This Cu overabundance agrees with the trend derived by Smith (1994) for this element in Hg-Mn stars.

Finally, Smith (1996) studied the Ga abundance in his sample of Hg-Mn stars and he found that Ga is overabundant in all the stars and that the Ga abundance is positively correlated with $T_{\rm eff}$. The +3.25 dex Ga overabundance of 3 Cen A well agrees with the trend pointed out by Smith (1996), but the only 1 dex enhanced Ga abundance of Feige 86 does not.

Fig. 10 compares the abundances of 3 Cen A and Feige 86 relative to the solar ones with those of the Hg - Mn stars derived from the literature. For Hg-Mn stars the limits for the B abundance are taken from Sadakane et al. (1985), those for C, N, O, P, S, Ca, Sc, Ti, V, Pt, and Hg abundances from Takada-Hidai (1991), while the limits for Mg, Al, Si, Cr, Mn, Fe, Co, Ni, Cu, Zn, and Ga abundances are taken from Smith (1993), Smith & Dworetsky (1993), Smith (1994), and Smith (1996). The chemical composition of 3 Cen A is similar to that of the Hg - Mn stars, with exception for Pt, which cannot be observed in 3 Cen A at the IUE dispersion. In Feige 86, the abundances of B, C, N, and slightly Hg are outside the limits observed in Hg - Mn stars. The light element underabundances could be related to Feige 86 belonging to the Pop II stars.

While for Hg-Mn stars and for the cooler Ap and Am stars several computations based on radiative diffusion mechanism (Michaud, 1970) were performed in order to explain the observed peculiarities, for stars hotter than 17000 K very few predictions are available in the literature. For these stars, the most studied element is He. The anomalous ^{3}He/^{4}He isotopic ratio observed in some Bp stars, and in particular in 3 Cen A, was explained by Michaud & Proffitt (1992) by means of diffusion driven by the light induced drift (LID). This new formulation of the diffusion theory seems to give more satisfactory explanations for the observed He isotopic abundances than the radiation driven diffusion (Michaud et al., 1979). However, only detailed diffusion computations for each element observed in 3 Cen A and Feige 86 could clarify whether the diffusion theory is able to predict the observed peculiar abundances.

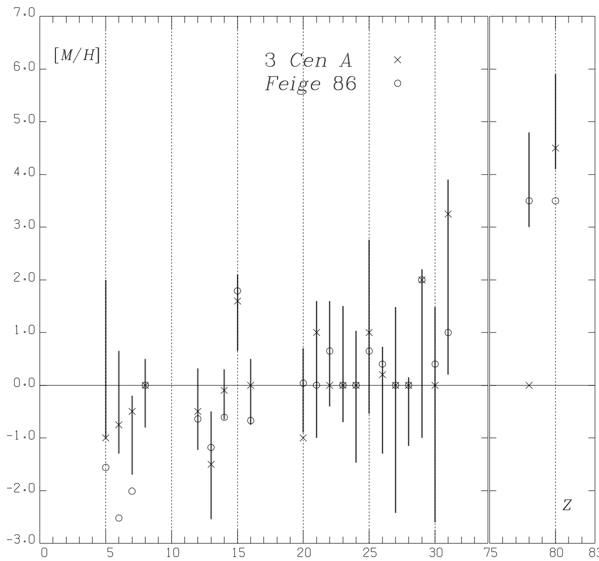

Fig. 10. The abundances of 3 Cen A (x) and Feige 86 (o) relative to the solar ones compared with those of the Hg-Mn stars. The vertical bars indicate the abundance range observed in Hg-Mn stars for the element with Z atomic number

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