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Spectroscopic and Photometric Investigation of the A 2 Ia–O Star HD 160529

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Summary. A simultaneous photometric (*uvby*) and high dispersion (12 Å/mm) spectroscopic investigation of the extreme galactic A-supergiant HD 160529 has been carried out. From large radial velocity variations, of an amplitude of 40 km/s, and from a variable splitting of the Ti II-, Fe II- and Cr II-lines of a maximal separation of 42 km/s, the existence of very pronounced time- and depth-dependent non thermal photospheric velocity fields was inferred. The measured intensity variations of the absorption lines of about 20% and the considerable photometric variations with an amplitude of 0.27 in y and of 0.18 in $(u-v)$ are explained by the action of these velocity fields. It is suggested that such variable velocity fields likewise provide and explanation for correlated line intensity and radial velocity-variations. The mass flux, coupled with the velocity field, is supposed to produce a chromosphere in HD 160529 by mechanical energy dissipation. The detected emission features of H_α, H_β, and of the Fe II-lines at λλ 5991, 6432 and 6516 (these Fe II-lines are known to occur in nova like variables in emission), as well as the absorption line He λ 5876 are considered as chromospheric in origin. A variability of the H_β-emission component, with changes from an inverse to a normal "P-Cygni" type profile, was found. The strong coupling of the line splitting and the intensity variations of the Fe II-emission lines was investigated.

Key words: A-supergiant — photometric variations — spectral variations — mass flux — chromosphere

I. Introduction

A number of photometric and spectroscopic observations of A-type supergiants have revealed variability in light intensity, line strengths, and radial velocities. Abt (1957) concluded that the variability in radial velocities was due to stellar pulsations of a complex character in A- and F-type supergiants. For the explanation of the empirical curves of growth for A-type supergiants very high (often supersonic) microturbulence-velocities were required by several authors. Rosendhal and Wegner (1970) recognized a correlation between line strength-variations and radial-velocity-variations in A-type supergiants. Groth (1972) principally could explain the differential and variable line shifts of different elements and ions in α Cyg (A 2 Ia) by assuming a velocity gradient in the atmosphere, variable with time.

Recently Pecker *et al.* (1973) and Thomas (1973) have developed a new general scheme of atmospheric structure. A universal prevalence of mass-fluxes in stellar atmospheres, caused by subatmospherically stored nonthermal kinetic energy, is asserted. Models with photospheric systematic velocities alone (no "turbulence") should predict the kind of observed line-broadening.

Chromospheres have to be expected not only for stars with solar-type convective sources of mechanical energy, but, with varying properties, should be very common as a result of the various prevailing nonthermal atmospheric velocity fields. A sufficient condition is the dissipation of some of the mechanical energy, associated with the mass-fluxes.

Direct observational evidence for a depth-dependant large-scale velocity field in an A-type supergiant was found in the extreme star HD 33579 (A 3 Ia–O; $M_v = -9.5$) in the Large Magelanic Cloud (LMC) (Wolf, 1972); namely asymmetric profiles of the absorption lines. Direct evidence for associated chromo-

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spheres was found in HD 33579 as well as in the brightest star in the Small Magellanic Cloud HD 7583 (A 0 Ia–O; $M_v = -9.3$) (Wolf, 1973), such as redshifted strong emissions in H_α, and, in the case of HD 33579, even some emission in the Ca II H and K resonance lines. Both stars were also found to be variable in intensity (Rosendhal and Snowden, 1971; Ardeberg, 1973).

To elucidate the relation between pulsational instabilities, velocity fields, and the chromospheres (which are thought to be dynamic rather than static structures) of A-type supergiants, simultaneous photometric and spectroscopic observations over a longer period are necessary. As the mentioned effects are generally increasing with luminosity, HD 33579 would be an ideal target star (also because of the knowledge of its absolute magnitude as a member of the LMC) if it was not prohibitively faint for extensive high dispersion spectroscopy. Therefore we have concentrated ourselves on HD 160529, an extreme A 2 Ia–O supergiant in the direction of the galactic center. This star was mentioned by Hiltner (1954) as being probably of higher absolute luminosity than α Cyg, and by Feast *et al.* (1960) as being perhaps comparable in absolute magnitude with HD 33579 of the LMC.

In Section II we present the spectroscopic and photometric observations for HD 160529. In Section III the results are discussed in connection with the atmospheric properties of HD 160529 with special emphasis on the atmospheric velocity fields and the associated chromospheric features.

II. The Observations

1. *Established Data*

The coordinates of HD 160529 are ($\alpha_{1900} = 17^h35^m.3$, $\delta_{1900} = -33°27'$), ($l^{II} = 355.°9$, $b^{II} = 1.°72$). HD 160529 has been classified as an extreme A-supergiant by various authors (Table 1).

Table 1. Spectral Classification of HD 160529

Spectral type	Source
A 2Ia$^+$	Hiltner (1954); Smith (1956)
A 3eIa – O	Bidelman (1954)
A 3Ia$^+$	Buscombe (1959)
A 2Ia – O	Feast *et al.* (1960)

Radial velocities were determined from low dispersion spectra by Wilson and Joy (1950) to $V_r = -34 \pm 3$ km/s and by Buscombe and Kennedy (1965) to $V_r = -36 \pm 2$ km/s. The *UBV*-magnitudes and the colour excess determined by Hiltner (1956) are: $V = 6.67$, $B - V = 1.28$, $U - B = 0.35$ and $E_{B-V} = 1.22$.

2. *Spectroscopic Observations*

32 coudé spectra in the blue ($3600 < \lambda < 4900$ Å) and red ($5400 < \lambda < 6700$ Å) region with a dispersion of 12.3 Å/mm have been taken with the ESO 1.52 m spectroscopic telescope on La Silla, Chile during 1970 to 1973 (Table 2). The type of evaluation for the different plates (equivalent width-, radial velocity-measurements, line profile-evaluation) is indicated in Table 2. The radial velocities[1]) were measured with the Grant-machine of ESO, Santiago, and the intensity tracings were obtained with the "Schnellphotometer-Curve-Follower-Equipment" of ESO, Santiago.

The radial velocities for different lines and groups of lines show large amplitudes of variations, of 30 and 40 km/s. These variations, which are discussed in III.2, are much larger than the mean errors, ± 2 to ± 4 km/s, as determined separately for the Ti II-, Fe II- and Cr II-lines.

[1]) Throughout this paper heliocentric radial velocities will be used.

Table 2. The spectrograms (dispersion 12.3 Å/mm; projected slit width on the spectrum 22.6 μ)

(1)	(2)	(3)	(4)	(5)	(6)		
					A	B	C
G 1131	0705	II a O	0h 43m	R	*	—	*
G 1138	0706	II a O	1h 00m	R	—	—	*
G 1429	0778	II a O	0h 41m	R	*	—	*
G 2721	1404	II a O	4h 0m	C	*	*	*
G 2723	1405	II a O	4h 3m	C	*	*	*
G 2939	1428	103 aF	2h 54m	W	*	—	—
G 2943	1429	103 aF	2h 18m	W	*	*	*
G 2947	1429	II a O	1h 46m	W	*	—	—
G 2948	1429	II a O	1h 39m	W	*	*	*
G 2949	1429	II a O	1h 22m	W	*	*	*
G 3110	1450	II a O	1h 54m	W	*	—	—
G 3111	1450	103 aF	50m	W	—	—	*
G 3119	1451	103 aF	1h 15m	W	*	—	*
G 3120	1451	II a O	47m	W	*	—	—
G 3128	1452	103 aF	1h 6m	W	*	—	*
G 3222	1492	103 aF	53m	W	*	*	*
G 3223	1492	II a O	48m	W	*	—	*
G 3223	1492	II a O	48m	W	*	—	*
G 3780	1759	103 aF	2h 15m	W	*	—	*
G 3781	1759	II a O	46m	W	*	—	—
G 3791	1761	II a O	2h 44m	W	*	—	*
G 3797	1762	II a O	2h 36m	W	*	—	*
G 4869	1807	II a O	—	W	*	—	—
G 4875	1808	II a O	36m	W	*	—	—
G 4902	1813	II a O	36m	W	*	—	—
G 4903	1813	103 aF	31m	W	*	—	*
G 4915	1843	103 aF	1h 21m	W	*	—	*
G 4916	1843	II a O	1h 46m	W	*	—	—
G 4972	1875	103 aF	2h 5m	W	*	—	*
G 4975	1876	II a O	2h 23m	W	*	—	—
G 4977	1877	103 aF	1h 30m	W	*	—	*
G 4978	1877	II a O	2h 10m	W	*	—	—

Column: Plate No.
(2) Julian Date minus 2440000
(3) Emulsion (IIa–O gives spectral range $3600 < \lambda < 4900$Å)
Emulsion (103a–F gives spectral range $5400 < \lambda < 6700$ Å)
(4) Exposure time
(5) Observer: R = Rickard; C = Campusano; W = Wolf
(6) Type of Evaluation: A = radial velocity measurement; B = equivalent width measurements; C = line profiles.

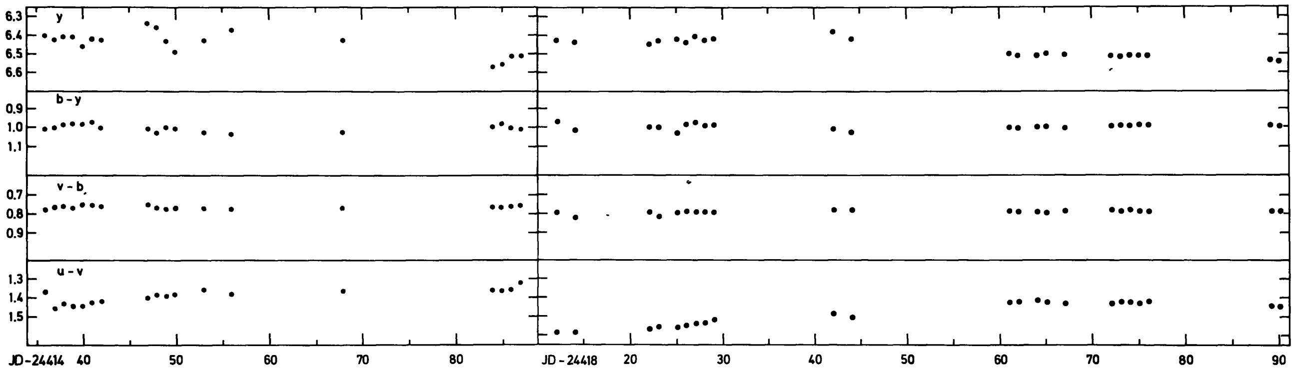

Fig. 1. The photometric measurements in the Strömgren *uvby*-system for the observing periods in 1972 and 1973

The equivalent widths (W_λ) of 180 lines were determined in the blue range from 4 spectra and of 15 lines in the red range from 2 spectra [for the W_λ-values see Campusano (1973)].

In order to search for a variability of the line intensities, we have combined the measurements from the 4 blue spectra to two pairs of $W_{\lambda 1}$ (from G 2721 and G 2723, JD 2441404-05) and $W_{\lambda 2}$ (from G 2948 and G 2949, JD 2441429), representing the observations of a time interval of 24 to 25 days. The mean errors for the $W_{\lambda 1}$- and $W_{\lambda 2}$-values were determined to 9% and 8% respectively for the weak lines ($W_\lambda \leqq 400$ mÅ), and to 5% in both cases for the strong lines. The systematic difference between the $W_{\lambda 1}$- and $W_{\lambda 2}$-values exceeds with about 20%, the mean errors significantly.

3. *Photometric Observations*

HD 160529 was observed on 18 nights in April–June, 1972, and on 23 nights in May–July, 1973. The observations were carried out with the ESO 50 cm telescope and with the Danish 50 cm telescope on La Silla, Chile, in the Strömgren *uvby* photometric system. The observed colours were transformed to the standard system of Crawford *et al.* (1970).

During the 1972 period the star was generally observed once a night (two or three measurements). The measurements are plotted in Fig. 1. The mean error for the measurements in one night is 0.01 mag in all colours. The range of fluctuations for HD 160529 in this period is 0.27 in y and 0.15 in $u-v$.

During the 1973 observing run a differential type of photometry was carried out, using the stars C 1 = HD 160461 ($V=7.47$, A 0) and C 2 = HD 160575 ($V=7.55$, B 8) as nearby comparison stars. In each observing night 2 to 10 observations of each of the comparison stars and of the program star were made, in the sequence C 1, S, C 2 (S = HD 160529).

For the nightly means of the measurements for HD 160529 see also Fig. 1. The range of fluctuations during this period was 0.16 mag in y and especially large in $u-v$ with 0.18 mag.

The average nightly mean errors of Δy, $\Delta(b-y)$, $\Delta(v-b)$ and $\Delta(u-v)$ for C_1–C_2, C_1–S and C_2–S are given in Table 3. The nightly variations of the corresponding Δ-values for C_1–S and C_2–S are generally larger with a larger scattering than for C_1–C_2 and with the same trend for C_1–S and C_2–S. This indicates that there might be small short term fluctuations of HD 160529 which are largest in $u-v$. But more systematic observations during entire nights were required to study this.

III. The Atmospheric Properties of HD 160529

1. *Curve of Growth Results*

With the equivalent width measurements separate curves of growth were constructed for the Ti II-, Fe II- and Cr II-lines. The empirical curves of growth were compared with the universal theoretical curves of growth (Unsöld, 1955). The resulting data for the excitation temperature $\left(\text{in the form } \Theta_{\text{exc}} = \frac{5040}{T_{\text{exc}}}\right)$, the Doppler linebroadening ξ_0 (thermal Doppler velocity and microturbulence parameter), and the broadening parameter $\log \frac{\gamma}{\Delta\omega_D}$ are given in Table 4. The parameters were determined separately for the $W_{\lambda 1}$- and $W_{\lambda 2}$-values.

Table 3. The differences in y and in the colours and the nightly mean errors for (C_1-C_2), (C_1-S) and (C_2-S). C_1 and C_2 are the comparison stars, S = HD 160529

	Δy	m.e.	$\Delta(y-b)$	m.e.	$\Delta(v-b)$	m.e.	$\Delta(u-v)$	m.e.
C_1-C_2	−0.084	0.0019	−0.218	0.0020	−0.060	0.0021	1.030	0.0025
C_1-S	0.996	0.0029	−0.881	0.0032	−0.563	0.0025	−0.098	0.0046
C_2-S	1.082	0.0035	−0.662	0.0033	−0.503	0.0034	−1.126	0.0046

Table 4. The curve of growth parameters of HD 160529, as determined from spectra taken at a time interval of 24 to 25 days. The two spectral sets are distinguished by $W_{\lambda 1}$ and $W_{\lambda 2}$

	Ti II		Fe II		Cr II	
	$(W_{\lambda 1})$	$(W_{\lambda 2})$	$(W_{\lambda 1})$	$(W_{\lambda 2})$	$(W_{\lambda 1})$	$(W_{\lambda 2})$
Θ_{exc}	0.65	0.65	0.63	0.63	0.65	0.65
ξ (km/s)	10.2	14.5	7.4	10.0	8.3	9.6
log $\gamma/\Delta\omega_D$	− 2.0	− 2.0	−2.0	− 2.0	−2.0	—2.0

According to the equivalent widths variations, the microturbulence parameter changes by 41% for Ti II, 30% for Fe II and 15% for Cr II. A possible explanation for this will be given in III.2. Turbulent velocity variations in A-type supergiants have been reported by various authors. The largest variations, exceeding a factor of two, were found by Buscombe (1972) in the case of the A 0 Ia-supergiant HD 92207.

2. *The Photospheric Velocity Phenomena*

a) The Balmerlines

In Fig. 2 the radial velocities for the Balmer-lines from H_γ to H_{10} are plotted for different spectra.

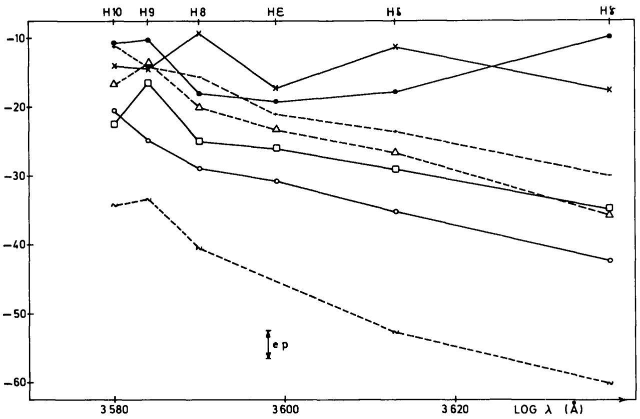

Fig. 2. The dependence of the radial velocity from the quantum number of the Balmer-lines H_γ to H_{10} for different Julian dates. The different symbols identify the Julian dates as follows: ○ JD 2440705, × JD 2440778, ○ JD 2441404, □ JD 2441420, + JD 2441450, △ JD 2441492, ~ JD 2441761. The velocity (km/s) is plotted on the *Y*-axis

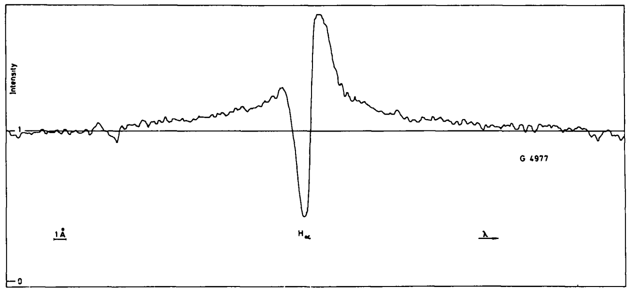

Fig. 3. Intensity tracing of H_α from spectrum Nr. G 4977

A strong variation in time must be stated. H_α and H_β were not incorporated, because they are obviously disturbed by emission components. The emission is very strong for H_α (see an example in Fig. 3).

Several authors have observed a progression of the radial velocity of the Balmer-lines with increasing quantum numbers in A-supergiants (cf. Aydin, 1972). A radial velocity progression of the Balmer-lines was also found on most of our spectra (see Fig. 2). Such a systematic progression in radial velocities can be simulated by a distortion of emission, which is decreasing with increasing quantum numbers because of the Balmer-decrement. Using theoretical profiles [calculated on the basis of a plan parallel model atmosphere in radiative equilibrium and LTE and of the Balmer-line broadening theory of Griem (1962)], the "Doppler" shift of the absorption components of H_α and H_β against the rest of the lines could be explained by distortion of emission, in the case of HD 7583 (Wolf, 1973). The small equivalent widths of H_β and H_γ (compared with the theoretical values) likewise could be explained by some superimposed emission.

In the case of HD 160529 we have direct observational evidence for this explanation. On the spectrum G 1131 (JD 2440705) the velocity is largest for H_γ, and on the same spectrum also a faint blue shifted emission in H_β was found. Note, that a blue shifted emission has never been observed during 1972 and 1973, neither in H_α nor in H_β. The radial velocity measurements for the emission- and absorption-components of H_β for different plates are given in Table 5. The variations in H_β for three spectra (JD 2440706, −1404, −1429) are shown in Fig. 4. The intensity tracings were adjusted to make the positions of the metallic lines coincide and it can be easily seen, how the center of the absorption component gets shifted as a consequence of the intensity variations of the emission component.

Because of the progression of the velocities with increasing quantum numbers due to decreasing distortion by emission, the time dependent velocity, in those photospheric layers in which the absorption Balmer-lines are formed, is determined from the higher Balmer-lines (H_8, H_9, H_{10}) only. Then we get an amplitude of photospheric velocity variations of 25 to 30 km/s.

Table 5. Radial velocities in km/s for the emission and absorption component of H_β

Julian Date (244−−−)	$H_{\beta_{em.}}$	$H_{\beta_{abs.}}$
0705	−62.1:	−14.6
0778	no emission	−17.7
1404[2]	6.1	−45.5
1420[3]	13.4	−44.1
1450[2]	14.0	−42.4
1492	11.6	−45.2
1761	2.4	−66.6

The exponent on the Julian Date indicates the number of measurements.

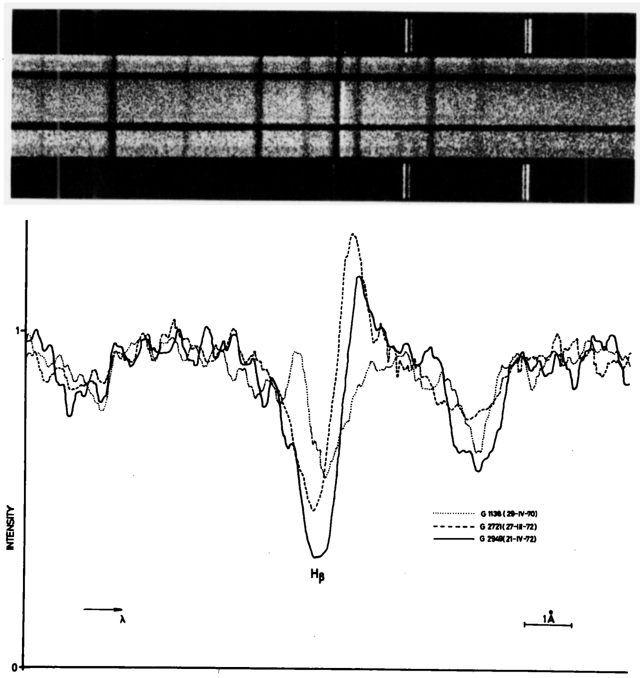

Fig. 4. Spectra and corresponding intensity tracings around H_β, showing considerable profile variations. Note the change from an inverse "P-Cygni" type profile on JD 2440705 to normal "P-Cygni" type profiles for the spectra, taken at later dates

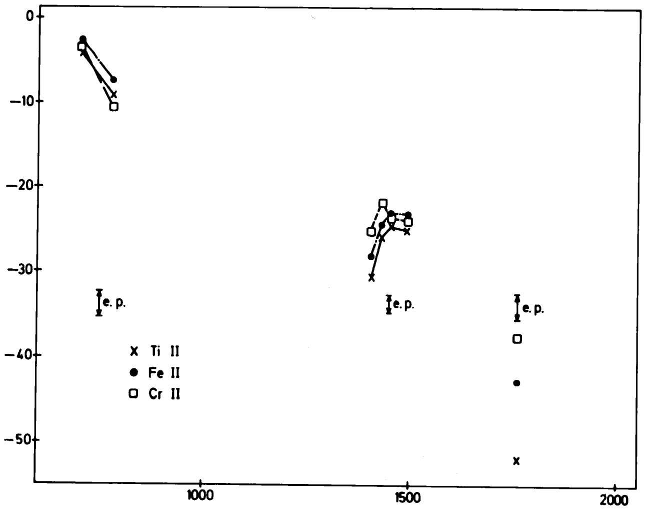

Fig. 5. The averages of the radial velocity measurements of the groups of Ti II-, Fe II- and Cr II-lines from spectra, taken in the time interval from 1970 to 1973. The velocity (km/s) is plotted against the time. The figures of the X-axis are the Julian date minus 2440000

b) The Radial Velocities of the Metallic Lines

If there is a depth-dependent radial velocity field, different radial velocities should be measured for lines originating in different optical depths. Groth (1972) gives a dependence on the lower excitation potential χ and the equivalent width of the line. Strong lines with a small value of χ are formed in the highest atmospheric layers, whereas weak lines with a large λ originate in deeper layers. Thus the lines of Table 6 were selected for defining line groups, which are representative for the velocities in certain atmospheric layers. In this sense the sequence Ca II–K, Ti II, Fe II, Cr II, Mg II, Si II represents the velocities of photospheric layers of increasing optical depth. The velocities for the line groups and for the Ca II–K and Mg II (λ 4481)-lines are plotted in Figs. 5 and 6.

Long term variations between the values of 1970 and 1973 with an amplitude of about 40 km/s can be stated.

There are also medium term variations within three months for each group, which exceed the mean error of the measurements.

The velocities of the Ti II-, Fe II- and Cr II-groups agree well for the observing periods 1970 and 1972. But the velocity differences are large in 1973 with 14 km/s between Ti II and Cr II. For an interpretation see the intensity tracings of a Fe II-line group on Fig. 7

Table 6. Data (λ, W_λ, $\chi_{r,s}$) of the Ti II-, Fe II-, Cr II- and Si II-, lines, which were used for defining the groups that provide the average velocities of Fig. 5 and 6. The same data are listed for the Ca II K- and Mg II (λ 4481)-lines

	mult.	λ (Å)	W_λ (mÅ)	$\chi_{r,s}$ (eV)
Ti II	87	4028.332	303	1.88
	105	4163.644	425	2.58
	41	4290.222	535	1.16
	20	4294.101	543	1.08
	41	4300.052	690	1.16
	41	4307.900	495	1.16
	19	4443.802	615	1.08
	50	4563.761	545	1.22
	82	4571.971	*563*	*1.56*
		average:	524	1.43
Fe II	27	4173.45	683	2.57
	28	4296.567	575	2.69
	37	4491.401	458	2.84
	38	4508.283	650	2.79
	37	4515.337	—	2.79
	37	4520.225	578	2.79
	38	4522.634	700	2.79
	37	4629.336	*609*	*2.79*
		average:	608	2.76
Cr II	44	4558.659	658	4.05
	44	4588.217	608	4.05
	44	4592.09	355	4.05
	44	4618.83	485	4.05
	30	4824.13	585	3.84
	30	4876.41	*388*	*3.84*
		average:	510	3.96
Si II	1	3853.657	440	6.83
	1	3856.021	755	6.83
	1	3862.592	692	6.83
	3	4130.884	*422*	*9.80*
		average:	577	7.57
Mg II	4	4481.228	913	8.83
Ca II	1	3933.660	1540	0.00

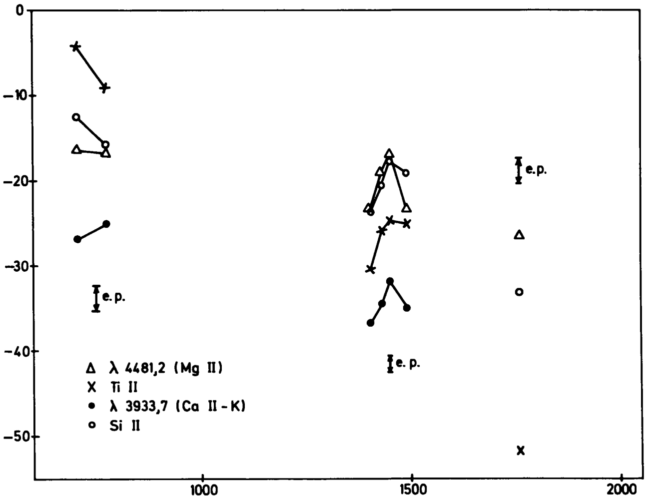

Fig. 6. Same as Fig. 5 for the Ti II-, Si II-line groups and for the lines Mg II (λ 4481) and Ca II-K

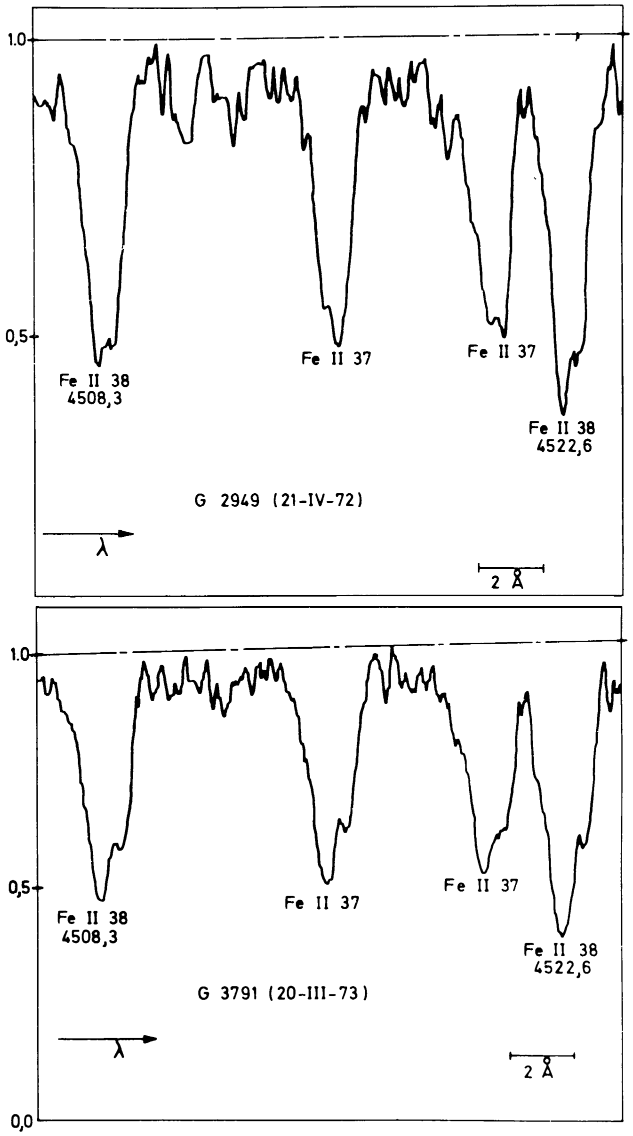

Fig. 7. Tracings of a group of Fe II-lines for two spectra, taken at a time interval of one year and showing strong profile variations. The lines from spectrum G 3791 exhibit some line splitting. The intensity scale is different for the two spectra

of a spectrum (G 2949) from 1972 and of the spectrum (G 3791) from 1973: The line profiles on G 3791 are asymmetric and the beginning of a line splitting can be seen, supplying direct observational evidence for the existence of a large-scale depth-dependent photospheric velocity field, which is variable in time. The line splitting, observed for Ti II, Fe II and Cr II is supposed to be caused by photospheric layers, moving relative to each others. A change of the velocity field can also be inferred from the profile changes; the blue wings are much flatter on the 1973 spectrum. The large difference between the radial velocities of the Ti II- and Cr II-line groups on G 3791 can then be understood, because the contributions from the different photospheric layers are different for the various groups, according to the individual excitation potentials. To our knowledge such a line splitting has never been observed before for Ti II, Fe II and Cr II in an A-supergiant. However, Thackerey (1962) has remarked on faint components of H_γ and H_δ in the A-supergiant HD 92207, and ascribed them to atmospheric mass motions or a surrounding shell rather than to the presence of a fainter star. Before we continue with the line splitting, we want to discuss the lines and groups of lines (Mg II λ 4481, Ca II K, Si II) of Fig. 6.

The velocity differences are generally larger here as a direct consequence of the larger differences in the excitation potentials and the equivalent widths of the lines involved. The velocities of Si II and Mg II behave similarly (similar $\chi_{r,s}$-values), but they differ from those of Ti II. Also their velocities relative to Ti II changed the sign between 1970 to 1972, i.e. *the different atmospheric layers, at which the different line groups are approximately formed changed the direction of their movement*. It is remarkable that the velocity variations of Mg II and Si II are smaller over the whole period. As these lines represent the deeper atmospheric layers, it means that the influence of the irregular oscillations of the star on the velocities is enhanced in the higher atmospheric layers.

Therefore, the velocity of the Ca II K-line (Ca II H was not incorporated because of distortion by H_ε), which represents the velocity of the highest, atmospheric layers in our consideration here, deserves special attention. The velocity of the Ca II K-line is always considerably shifted against those of the rest of the lines, in the sense that the outer-material is moving away from the star with a higher velocity. Ca II K is certainly disturbed by interstellar absorption, which is strong for HD 160529, as can be seen from the interstellar absorption features such as the ones at λ 4430 Å and λ 6284 Å (Fig. 8) and the interstellar Na I D_1 and D_2 lines (Fig. 9). But on the other hand a shift

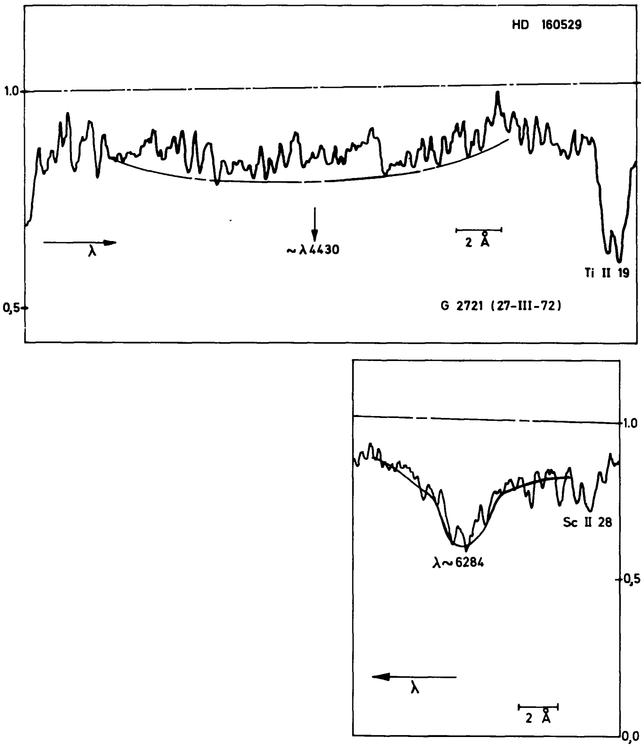

Fig. 8. The interstellar absorption features at λ 4430 Å and λ 6284 Å

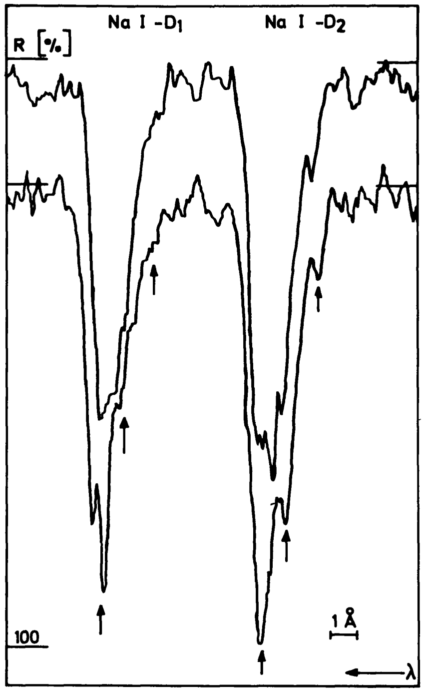

Fig. 9. The Na D-lines of HD 160529

of the velocities of the Ca II H and K lines against those of the rest of the lines has been observed for many supergiants. The first observation of this kind was a shift of −6.8 km/s in β Ori (B 8 Ia) (Adams and McMc Comarck, 1935). Thackeray (1962) measured shifts of −13.5 km/s for HD 33579 in the LMC and −9.3 km/s for HD 7583 in the SMC, whereas Wolf (1972, 1973) found shifts of −21 km/s and −3 km/s for the same stars, indicating a variability of these shifts with time in extreme A-supergiants (Thackeray, 1972). From cepheids it is known (cf. Jacobsen, 1956; Häfner, 1973), that the K-line has an absolute higher velocity in the maximum and minimum of the light curve than the rest of the metal lines. Variations of the velocity shift in time are also present in the case of HD 160529.

The Na I D-lines (Fig. 9) have a rather complicated structure with three different components (recognizable on nearly all the spectra) with the corresponding radial velocities −18 km/s, −56 km/s and −111 km/s. The individual measurements are given in Table 7. The absorption in the center of Na I–D_2 is 100%. Sodium is practically completely ionized in the photosphere of an extreme A-type supergiant. Thus the complicated structure of the sodium lines presumably has to be ascribed to interstellar gas or/and circumstellar shells with considerable velocities. Wallerstein (1970) has measured one component of −61 km/s of the sodium lines in HD 160529, interpreting it by gas flowing out from the galactic center rather than by a circumstellar shell.

c) The Line Splitting of the Ti II-, Fe II- and Cr II-lines and Profile Variations

The occasional line splitting is one of the most striking spectral characteristics of HD 160529, which cannot be explained by assuming that HD 160529 is a double lined variable binary. For a binary system one would expect a periodic light curve. The photometric variations (Fig. 1) are rather irregular and irregular pulsations are a more likely mechanism here. A correlation of the intensity tracings of JD 2441875, 2441877 with the photometric observations of that time reveals, that the strong line splitting in those spectra is coupled with a faint visual magnitude, whereas rather the contrary should occur if HD 160529 was for example an eclipsing binary system. Another point is a strong correlation of the appearance of the line splitting with the appearance of certain Fe II-emission lines, namely Fe II 40 (λ 6432, λ 6516) and Fe II 46 (λ 5991). These lines which are discussed later are known to appear in emission in nova like variables (Meinel *et al.*, 1968) and likewise should result from the irregular pulsations, supposed to cause the splitting of the absorption lines.

The spectra in Fig. 10 show the variation of this splitting in time for the Fe II 74 line (λ 6457). The intensity tracings in Fig. 11 of the Fe II 74 lines (λλ 6238, 6247, 6457) reveal profile changes going through asymmetries and culminating in a splitting with a velocity difference of 42 km/s of the two components at maximum separation. The measurements for the elements in those spectra, which show

Table 7. Radial velocity measurements (km/s) from spectra showing some line splitting. Averages are given for the Ti II-, Fe II-, Cr II-, Si II and Mg I-lines. In the case of H_α the emission- and absorption component is measured, whereas H defines the average velocity for the H_8-, H_9- and H_{10}-absorption lines. Fe II Em. is the average from the three emission lines at $\lambda\lambda$ 5991, 6432, 6516

JD 244–	1450	1452	1808	1813	1843	1876	1877
Ti II v_1	– 52.2	– 51.9	– 46.6	– 44.7	– 43.8	– 49.6	– 48.7
v_2	– 10.2	– 8.8	– 22.1	– 15.5	– 14.0	– 12.8	– 13.4
Δv	– 42.0	– 43.1	– 24.6	– 29.2	– 29.8	– 36.8	– 35.3
v_a	—	—	– 37.6	– 36.7	—	—	—
Fe II v_1	– 50.5	– 50.8	– 43.6	– 44.5	– 42.2	– 51.8	– 52.4
v_2	– 8.1	– 11.6	– 18.4	– 15.9	– 11.4	– 10.2	– 10.1
Δv	– 42.4	– 39.1	– 24.4	– 28.1	– 30.8	– 41.6	– 42.3
v_a	—	—	– 38.4	– 35.6	—	—	—
Cr II v_1	– 49.6	– 48.3	– 43.6	– 36.0	– 44.3	– 43.4	– 47.9
v_2	– 9.9	– 11.0	– 20.1	– 11.1:	– 17.4	– 11.5	– 13.1
Δv	– 39.7	– 37.3	– 23.5	– 24.9:	– 26.9	– 31.9	– 34.8
v_a	—	—	– 33.1	– 36.0	—	—	—
H v	– 35.0	– 32.9	– 28.9	– 31.2	– 23.2	– 28.0	– 27.7
Si II v	– 33.8	– 35.0	– 25.8	– 27.1	– 16.2	– 20.2	– 20.9
Mg I v	– 33.2	– 39.5	– 29.2	– 27.7	– 17.3	– 18.5	– 18.6
Mg II v (4481)	– 18.6	– 23.2	– 25.8	– 21.8	– 15.8	– 18.6	– 20.4
Ca II v	– 49.0	– 50.5	– 47.5	– 45.7	– 48.5	– 52.5	– 59.0
v_f	—	—	—	—	– 8.9	– 8.2	– 14.0

JD 244–	1450	1452	1759	1813	1813	1843	1875	1877
H_α v_E	+ 18.2	+ 11.7	+ 14.7	+ 15.7	+ 17.0	+ 18.5	+ 7.1	+ 16.4
v_A	– 45.2	– 46.8	– 46.9	– 63.9	– 50.9	– 54.5	– 54.6	– 51.7
Fe II Em v_{Em}	– 25.1:	– 38.7:	– 24.2	—	—	– 30.3	– 28.2	– 26.4
He I 5876 v	– 18	– 16	– 37	– 18	– 25	– 13	– 13	– 15
NaD_1 v_1	– 18.8	– 19.5	– 14.9	– 21.7	– 13.1	– 13.0	– 19.5	– 14.0
v_2	– 59.0	– 48.3	– 48.4	– 65.6	– 43.0	– 44.2	– 52.9	– 57.3
v_3	–114.4	–120.5	–117.3	– 97.5	–109.4	–110.4	– 89.2	–108.4
NaD_2 v_1	– 21.8	– 21.9	– 17.2	– 25.9	– 13.7	– 19.0	– 18.1	– 19.0
v_2	– 60.9	– 56.6	– 61.5	– 75.7	—	– 53.3	– 60.6	– 53.2
v_3	—	–113.7	—	–115.3	–114.3	–106.7	–120.0	–112.7

Explanation of symbols:

v_1, v_2, v_3 = velocity of the different components of the absorption lines.
v = velocity of absorption lines.
Δv = relative velocity between the two components of the splitted Ti II-, Fe II-, and Cr II-lines.
v_a = average velocity for both components, when the splitting is not very pronounced on JD 2441808 and –1813.
v_f = velocity of a faint absorption component of Ca II K, observed on three plates.
v_E, v_A = velocity of the emission — and absorption — components of H_α.
v_{EM} = average velocity of the Fe II emission lines.

some line splitting, are given in Table 7. (Also included in Table 7 are the average radial velocities for the absorption lines of the elements and ions with no splitting, for the Fe II-emission lines, and for the H_α emission and absorption components.) On the spectra from JD 2441875 to –1877 both components of the Ti II-, Fe II- and Cr II-lines are very pronounced and of comparable intensity.

At JD 2441807, –1808, –1813 a splitting is present only in some lines; the second component V_2 is very faint, and only by the use of the Grant oscilloscope with the line profile display, it was possible to measure those faint components. For most of the lines only an asymmetry is recognizable there. In JD 2441450–1452 the second component was also rather faint, but both components were separated by $\Delta v = 40$ km/s. The separation of the two components $(v_1 - v_2)$ is largest for the Ti II- and Fe II-lines and always some km/s less for the Cr II-lines. It is remarkable that the whole absorption feature on JD 2441808–1813, when only slight splitting was observed, provided an average velocity v_a for Ti II, Fe II and Cr II of –36 km/s in perfect accordance with radial velocity determinations by Wilson and Joy (1950) of $v_r = -34$ km/s and by Buscombe and Kennedy (1965) of $v_r = -36$ km/s.

The fast components, v_1, of the Ti II-, Fe II- and Cr II-lines show the same kind of variations and as an average also similar absolute velocity values as the

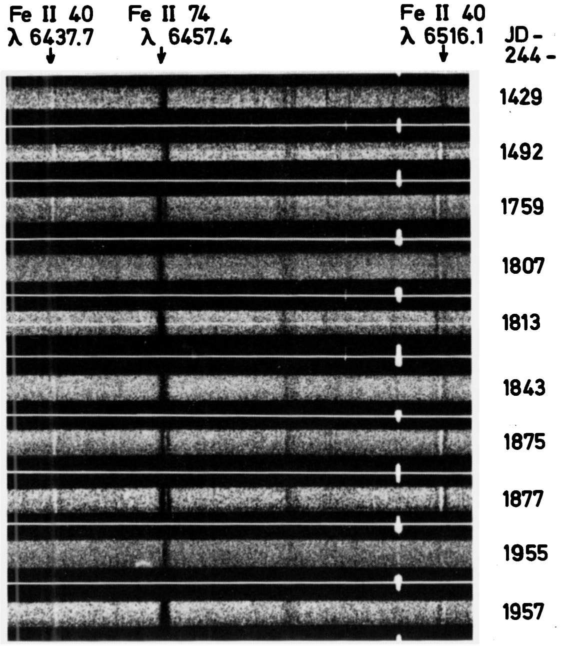

Fig. 10. Spectra for different Julian dates, showing the variations of the line splitting and of the intensity of the Fe II 40 lines at λ 6516, which appears sometimes in emission. The strong correlation between the amount of the line splitting and the intensity of the emission line is evident

Ca II K-line, indicating that the fast components are formed in the outer photospheric layers. But note, that on JD 2441877 there is a rather big difference of −10 km/s. On JD 1441843, –1876, –1877, when the line splitting is at maximum, there is also a faint red-shifted absorption in Ca II K (for velocities see Table 7), not observed on the spectra taken on earlier dates.

The Mg II (λ 4481)-, Mg I- and Si II-lines are never splitted; they are formed in deeper photospheric layers. But at least the Si II-lines show profile and intensity-variations (Fig. 11).

In connection with the line splitting and profile variations in HD 160529, the microturbulence problem in A-supergiants must be considered. For an interpretation of the empirical curves of growth of A-supergiants often very high values of the microturbulence parameter have been postulated. Microturbulence, which was first introduced by Struve and Elvey (1934), has been frequently criticized during the last few years.

It was proposed by Thomas (1973) that models including non-LTE effects and large scale mass fluxes can predict the kind of observed line intensities. Auer and Mihalas (1972) e.g. described the spectral properties of OB-stars with non-LTE models and no microturbulence at all. Kudritzky (1973) has emphasized, that non-LTE effects are also important in extended A-supergiant atmospheres. In the case of the sun, Oster and Ulmschneider (1973) and Shine and Oster (1973) have pointed out, that at least a significant

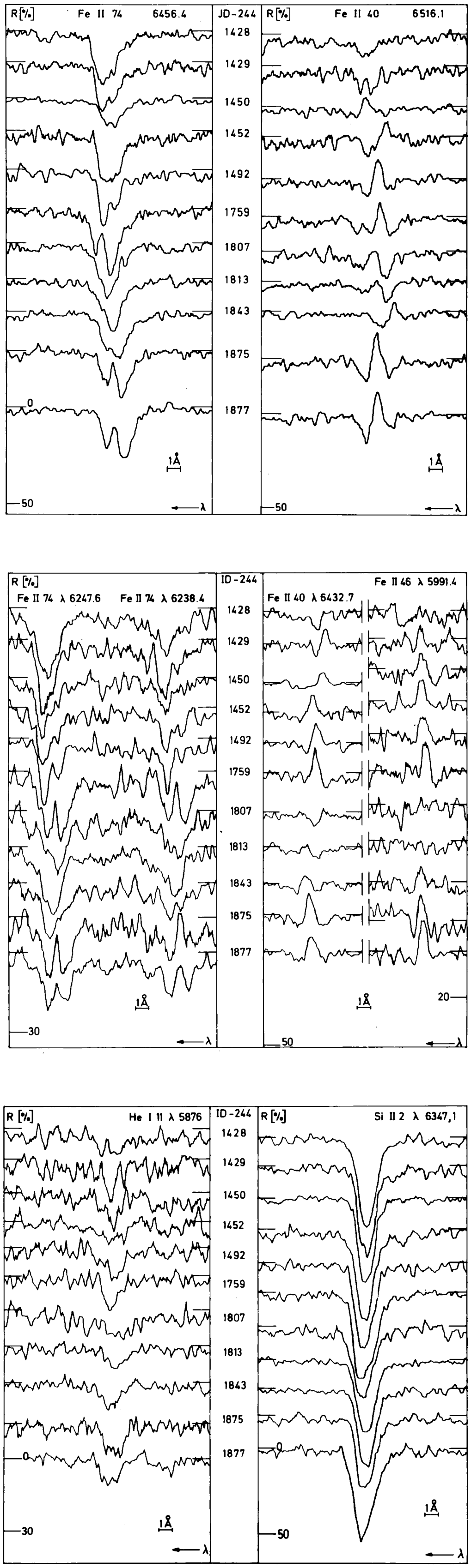

Fig. 11. Intensity tracings of several absorption- and emission-lines of HD 160529 from spectra, taken at different Julian Dates; details in the text

fraction of the apparent microturbulent velocities could be identified with macroscopic motions in the form of acoustic waves. It was shown by Simmoneau (1973) that macroscopic photospheric velocity fields can produce broad and even symmetric profiles without any microturbulence.

The radial velocity measurements and still more the line splitting have proved the existence of variable large scale velocity fields in HD 160529. Line intensity variations, often found in A-supergiants, and also measured in the present case (III.1), can be caused by variations of a depth-dependent large scale velocity field; it is in the present extreme case, that such variations can be seen directly from profile variations (Fig. 11). Finally, a correlation of line intensity variations with radial velocity variations, as found by Rosendhal and Wegner (1970), can likewise be explained by the action of depth-dependent large scale velocity fields alone, without invoking microturbulence variations. Direct observational evidence is provided in Fig. 7, for example. The lines from the spectrum G 3791, where some splitting is indicated, are obviously broadened by enhanced large scale mass fluxes (compared with the spectrum G 2949). The centers of gravity of the lines, get shifted simultaneously by these changes of the differential velocity field. Note, that it is only by the indicated splitting and profile changes that we directly recognize large scale mass fluxes as origin for the enhanced line broadening.

3. *The Photometric and Spectroscopic Variations*

On the basis of our curve-of-growth results, we estimated the effective temperature of HD 160529 to be approximately $T_e = 8800°$. This was done by ascribing the excitation temperature to an optical depth $\tau = 0.1$ in the atmosphere and comparing with strict hydrostatic LTE-models with the gravity value $\log g = 1$ (our curve of growth analysis gave $\log g = 1.1$). The observed variations in visual magnitude, y, could be explained by irregular temperature variations of the order of $\Delta T = 700°$. However, there are other effects, correlated with the spectroscopic variations, that affect the brightness as well as the colours. The percentage of absorbed energy in the absorption lines of an A 3 Ia-supergiant is about 5% in the visual. Assuming that during the maximum splitting twice of this amount was absorbed in the absorption lines in the visual and the whole redistributed flux would appear elsewhere in the spectrum outside the y-range, one would at maximum get variations of $\Delta y = 0.07$. There is, in fact, a correlation indicated between the brightness variations and the line splitting, in the sense that the star becomes fainter when additional line blanketing by splitting occurs. On JD 244 1449, –1452 some line splitting was observed; from Fig. 1 it can be seen, that during this time the star showed rapid photometric variations, but was rather faint. Little splitting was observed around JD 244 1808–1813–1843 and the star was rather bright at that time, whereas it was faint around JD 244 1875, –1877 when the observed splitting was at maximum.

Presumably the most important effect, responsible for the observed brightness- and colour-variations, specially in $(u-v)$, are continuum variations caused by the variations of the depth-dependent velocity field. By these variations the electron pressure of the atmospheric levels at which the continuum is formed, is also strongly affected and is changing from moment to moment. Especially sensitive to electron pressure variations in an A-star is the population of the second quantum level of the hydrogen. Thus we expect in particular variations of the Balmer-discontinuity, or equivalently in $(u-v)$, which are in fact seen. Groth (1972) has shown that differential variations of the order of 20 km/s of the photospheric velocity field of a star with T_e, $\log g$ parameters similar to HD 160529, can produce changes in the Balmer-discontinuity $D = \log \frac{F_\lambda > 3650}{F_\lambda < 3650}$ of $\Delta D = 0.09$. ($F_\lambda > 3650$ is the flux of the long wave length side and $F_\lambda < 3650$ is the flux on the short wave length side of the Balmer-jump.) Variations of D of this size are observed in HD 160529, and on the other hand the observed variations in the photospheric velocity field (radial velocity variations and line profile variations) are sufficient for producing these photometric variations.

4. *The Chromosphere of* HD *160529*

Formerly the existence of chromospheres was thought to be restricted to stars with solar type convection sources. Effective ionization convection zones do not exist in A stars. On the other hand strong H_α-emission features of varying properties have always been found in high luminosity A-supergiants. In Fig. 12 H_α is presented for some of the most extreme southern hemisphere A- and B-supergiants. The spectra were taken with ESO 1.52 m spectroscopic telescope of La Silla, Chile, during 1972 and 1973. H_α-emission features in A-supergiants are also discussed in Rosendhal's (1973) recent survey of H_α-emission in early type high-luminosity stars. Emission in H_α in the Magellanic Cloud A-supergiants HD 33579 and HD 7583 was ascribed to the existence of a chromosphere by Wolf (1972, 1973). In the case of HD 7583 a tentative chromospheric model was worked out. In HD 33579, in addition to a strong redshifted emission in H_α, an emission core in Ca II H and K was detected. This is universally accepted as an evidence for the presence of a chromosphere.

Pecker *et al.* (1973) and Thomas (1973) have argued that chromospheres have to be expected in a great variety of stars (if not in all). They define a chromosphere as that region of the stellar atmosphere, where radiative

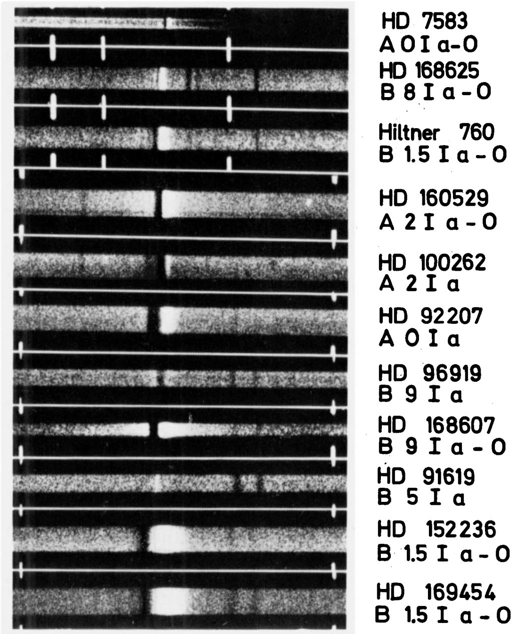

Fig. 12. The H_α-emission features of some extreme southern hemisphere A- and B-supergiants. Note, the dispersion is 31 Å/mm for the first three spectra, but 12.3 Å/mm for the rest of the spectra

equilibrium no longer holds, because of the presence of a mechanical energy dissipation term. In HD 160529 we expect strong chromospheric effects because of dissipation of some of the mechanical energy associated with the mass fluxes. One of the most prominent spectroscopic features of HD 160529 is the "P-Cygni" type H_α-emission with extremely broad wings, which can be traced up to a distance of about 20 Å from the line center (Fig. 3). It is very likely, that this H_α-emission is variable in time, but it is difficult to study this from our spectra, as the strong emission component is normally overexposed when the rest of the spectrum is well exposed. A variability of the H_β-emission component was already mentioned in III.2a (Fig. 4). The H_α "P-Cygni" type profile of A-supergiants is sometimes interpreted as due to very extended envelopes with considerable mass-loss. As already pointed out under III.2a, we believe that the absorption Balmerlines are photospheric and that it is the distortion by emission, that simulates the blue shift of the H_α- and H_β-absorption components. The origin of the H_α- and H_β-emissions is supposed to be chromospheric. A possible mechanism could be the one proposed by Wolf (1973) to explain the "P-Cygni" profile of H_α in HD 7583: Material is accelerated outward by shock waves; but it does not reach the escape velocity and has to return to the star's surface, where the material collides with the denser atmospheric layers and where part of the mechanical energy gets dissipated. Indeed, none of the measured radial velocities exceeds the escape velocity, which for HD 160529 is about 200 km/s.

An inverse "P-Cygni" profile of H_β, as observed on JD 2440705 (Fig. 4) was never observed again during 1972/1973. Therefore, it must be correlated with an event of a much shorter time scale than the mechanism, responsible for the normal "P-Cygni" profile, found in the rest of the spectra. It is attractive to consider that this emission was produced on the front of an outward running shock wave, moving with a relative velocity of 50 km/s through the star's atmosphere. The time scale, on which such a wave will travel through the atmosphere can be estimated. The radii of HD 7583 and HD 33579 were determined to be about 300 solar radii. If we accept the same value for HD 160529 and if we make further the reasonable assumption for an A-supergiant that the height of the atmosphere is about 10% of the radius of the star, then the atmosphere has an extension of about 2×10^7 km. A disturbance, moving with a velocity of 50 km/s, as measured for the blueshifted H_β component on JD 244075, then needs about 5 days to pass through the whole atmosphere. Similar calculations yield for the mass flux, correlated with the fast component of the splitted Ti II-, and Cr II-lines, a total traveling time through the atmosphere of about 7 days. In fact, the splitting sensitive lines changed completely within a one month interval (Fig. 11) (for example between JD 2441759 and –1877 or JD 2441843 and –1875), but the splitting did not markedly change between the two days JD 2441875 and –1877.

Direct observational evidence for the coupling of the chromosphere with the photospheric mass fluxes is supplied by the strong correlation between the amount of the line splitting and the intensity of the Fe II emission lines at λλ 5991, 6433, 6516 (Figs. 10 and 11). Whenever some splitting appears, the intensity of these emission lines increases and is at maximum when the splitting is at maximum. As pronounced splitting is obviously a sign of enhanced mass fluxes, consequently more energy dissipation occurs in the chromosphere. Thus an enhancement of the chromospheric features, like of the three Fe II-emission lines in the present case can be understood. As this occurs without any recognizable retardation, it supports our opinion, that these emissions take place in an atmospheric region in the very vicinity of the photosphere (i.e. the chromosphere) rather than in a very extended shell.

The presence of the He I λ 5876-line (Fig. 11) in the spectrum of HD 160529, a star with the parameters $T_e = 8800°$ and $\log g = 1.1$, is somewhat surprising, because the $2\,^3P$-level (20.87 eV) of He I, from which the line originates, cannot be populated significantly in a photosphere of a star with such a low temperature. Interpreting this He-line as photospheric would provide a He-abundance for this star, which is too high by more than a factor of 100, compared with the cosmic He-abundance $\log \varepsilon_{He} = 11.10$ (normalized to $\log \varepsilon_H = 12$ for hydrogen). Thus we propose that most of this

He-absorption line is also chromospheric in origin, an interpretation which was also given for the He I-lines observed in HD 7583 (Wolf, 1973). In the chromospheric region the temperature is high enough for a sufficient population of the 2^3P level of He I. The intensity of the He-line at λ 5876 (Fig. 11) is variable. The correlation with the splitting is not as clear as in the case of the Fe II-emission lines, but nevertheless it can be stated, that the line is especially intensive on JD 2441875 and −1877, when also the splitting is at maximum.

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References

Abt, H. A. 1957, *Astrophys. J.* **126**, 138
Adams, W. S., Mc Cormack, E. 1935, *Space J.* **81**, 119
Ardeberg, A. 1973, unpublished
Auer, L. H., Mihalas, D. 1972, *Astrophys. J. Suppl.* **205**, 193
Aydin, C. 1972, *Astron. & Astrophys.* **19**, 369
Bidelman, W. P. 1954, *Astrophys. J. Suppl.* **1**
Buscombe, W. 1959, Mem. Comm. Observ., Mt. Stromlo, Min. 3
Buscombe, W., Kennedy, P. 1965, *Monthly Notices Roy. Astron. Soc.* **130**, 281
Buscombe, W. 1973, *Astrophys. Space Sci.* **23**, 431
Campusano, L. 1973, Thesis, Universidad de Chile
Crawford, D. L., Barnes, J. V., Golson, J. C. 1970, *Astron. J.* **75**, 624
Feast, M. W., Thacheray, A. D., Wesselink, A. J. 1960, *Monthly Notices Roy. Astron. Soc.* **122**, 337
Griem, H. R. 1962, *Astrophys. J.* **136**, 422
Groth, H. G. 1972, *Astron. & Astrophys.* **21**, 337
Häfner, R. 1973, Thesis, Universitäts Sternwarte München
Hiltner, W. A. 1954, *Astrophys. J.* **120**, 41
Jacobsen, T. S. 1956, *Publ. Domion Astrophys. Obs. Victoria* **10**, 145
Kudritzki, R. P. 1973, *Astron. & Astrophys.* **28**, 103
Meinel, A., Aveni, A., Stockton, M. 1968, Catalog of Emission Lines in Astrophysical Objects, Univ. of Arizona
Oster, L., Ulmschneider, P. 1973, *Astron. & Astrophys.* **29**, 1
Pecker, J. C., Praderie, F., Thomas, R. N. 1973, *Astron. & Astrophys.* **29**, 289
Rosendhal, J. D., Wegner, G. 1970, *Astrophys. J.* **162**, 547
Rosendhal, J. D., Snowden, M. S. 1971, *Astrophys. J.* **169**, 281
Rosendhal, J. D. 1973, *Astrophys. J.* **186**, 909
Shine, R. A., Oster, L. 1973, *Astron. & Astrophys.* **29**, 7
Simonneau, E. 1973, *Astron. & Astrophys.* **29**, 357
Smith, E. van P. 1956, *Astrophys. J.* **124**, 43
Struve, O., Elvey, C. T. 1934, *Astrophys. J.* **79**, 409
Thackeray, A. D. 1962, *Observatory* **82**, N° 930, 207
Thackeray, A. D. 1972, private communication
Thomas, R. N. 1973, *Astron. & Astrophys.* **29**, 297
Unsöld, A. 1955, Physik der Sternatmosphären, Ind. Ed. Springer, Berlin-Göttingen-Heidelberg
Wallerstein, G. 1970, *Publ. Astron. Soc. Pacific* **82**, 5
Wilson, R., Joy, A. 1950, *Astrophys. J.* **111**, 221
Wolf, B. 1972, *Astron. & Astrophys.* **20**, 275
Wolf, B. 1973, *Astron. & Astrophys.* **28**, 335

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