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OBSERVATIONS OF O AND Of STARS

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SUMMARY

Spectrograms with a dispersion of 16.2A°/mm covering the spectral range λ3300 to λ4900 were obtained for three early O stars and three early Of stars. Detailed line profiles of selected hydrogen and helium lines were obtained, and equivalent widths of nearly all visible lines were measured. Comparison of the spectroscopic properties between Of stars and O stars suggest that Of stars have lower surface gravities than do O stars. Comparison of their photometric properties confirms this suggestion. Hence, present temperatures scales for O5-O8 stars may possibly be in error because they do not take into account the effect of gravity in determining spectral type. In addition, the spectra suggest that atmospheric models of Of stars should take into account spherical and hydrodynamic effects.

Key Words: O stars - line profiles - spectral classification

I. INTRODUCTION

One method of deducing an approximate value of the temperature of an O star is to estimate the spectral type of the star and then use some temperature scale which relates spectral type to effective temperature. The standard system of spectral classification (Petrie 1947) uses the equivalent-width ratios W(HeI)/W(HeII) and W(HI)/W(HeII) as spectral-type criteria. It is based on the premise that with increasing temperatures, the HeII lines appear and increase in strength, while the Balmer lines of HI and the HeI lines decrease in strength. Spectral types of Of stars are also estimated in the same way. These stars have O-type absorption spectra plus emission lines of NIII at λ4634, λ4640-1, and sometimes HeII at λ4686. Actually, at high dispersion, the spectra of almost all O stars show NIII emission, so the Of designation is assigned to these stars where the emission is strong enough to be noticeable at lower dispersions.

The system of spectral classification does not take into account possible variations in luminosity and gravity among O stars, because it is generally believed that such differences must be too small to detect or calibrate. Underhill (1955) concluded that the range of absolute magnitudes among O and Of stars obtained from m-c_1 photometry is only ± $0^m.35$ about a mean magnitude, $M_V = -4.2$. The small range in luminosity has been interpreted as an indication of a correspondingly small range in surface gravity, which comes about because an O-type supergiant (in the sense of having a log g <3.0) cannot exist because of the effects of radiation pressure. Spectroscopic observations seemed to confirm the small range in gravity. Underhill was unable to find any correlation between the strength of HI lines and absolute magnitude, and she noted that this lack of correlation is consistent with the views that (1) differences in gravity among O stars are only an order of magnitude and (2) the shapes of HI lines in hot stars are not primarily determined by Stark effect, but rather by thermal Doppler effect and radiation plus collision damping of the dispersion type (Underhill 1951).

In the past 15 years, observational and theoretical advances have made possible a re-evaluation of the spectroscopic and photometric differences among O stars. First, numerous photometric observations of O stars in clusters on the UBV system have enabled more precise determinations of absolute magnitude, and finer distinctions in M_V can now be detected than were previously possible. Secondly, realistic model atmospheres and line-broadening theories now enable a quantitative interpretation of observed line profiles. Calculations of line profiles in hot stars (e.g. Heap 1970) show that differences in gravity less than an order of magnitude should still be detectable. Finally, line-profile data obtained from high-dispersion spectra (e.g. Aller and Jugaku 1969, Peterson and Scholz 1971, Buscombe 1970) now enable a finer, more critical comparison of the spectroscopic properties of O and Of stars than was possible from equivalent-width data.

This paper reports an attempt to re-evaluate differences in the atmospheric properties among early O stars, and its main conclusions are (1) that variations in gravity do exist among O stars, with Of stars having the lowest gravities in the group, and (2) that these variations may seriously affect the relationship between spectral type and temperature. Sections 2 and 3 present arguments for a variation in gravity which is great enough to affect the spectral features which are used to estimate spectral type. Section 4 attempts to evaluate the effect of gravity on the temperature scale of O and Of stars derived from spectral type.

2. SPECTROSCOPIC COMPARISONS

In order to examine the extent of spectroscopic differences among O stars, high-dispersion spectrograms of three O stars and three Of stars were obtained. Table I gives information concerning the choice of stars. Successive columns list the HD number, spectral type, apparent visual magnitude, the association to which a star belongs, absolute visual magnitude, the measure of line broadening expressed as turbulent velocity, and references to previous spectroscopic studies. All these stars are O5 or O6 stars, except possibly HD 46223, which has also been classified O4 by Morgan, Hiltner, Neff, and Garrison (1965), on the basis of its weak HeI lines. On this basis, the spectrum of HD 15570 should be classified as O4f since its photographic spectrum shows no evidence of HeI.

Two pairs of stars -- HD 15570, HD 15629 and HD 46223, HD 46150 -- belong to the same clusters of known distances, so their absolute magnitudes should be good to a magnitude and their relative luminosities well determined. In each pair, one star is an O star while the other is an Of star, so they are useful in contrasting the spectroscopic properties of O and

and Of stars.

All the spectrograms were obtained in November 1968 by D. M. Popper at the coudé focus of the 120-inch telescope at Lick Observatory. All spectra have a dispersion, D = 16.2A°/mm, and all were widened to 0.5 mm. Calibration strips, placed on either side of the stellar spectrum enable an intensity calibration at any desired wavelength. The plates are baked Eastman Kodak IIaO emulsion with a resolution of about 20 microns, which corresponds to 0.3A° at this dispersion. Tracings of weak lines of the comparison spectrum show that the instrumental profile has a Gaussian shape whose half-width is 0.3A°. This resolution is sufficient to deduce line profiles of Stark-broadened lines, which are several angstroms wide at half-intensity.

All the spectrograms were traced with UCLA's Grant Mark III microphotometer in a density mode. Densities of the calibration strips and the stellar spectral profile perpendicular to the direction of dispersion were recorded at four wavelengths, $\lambda 3600$, $\lambda 4100$, $\lambda 4350$, $\lambda 4650$. The background density was recorded at the wavelength of each of the lines measured. The level of the continuum was placed on the basis of the best straight line through the continuum up to 50A° on either side of the line in question. The long baseline was necessary because the early members of the HI Balmer series of several stars show emission wings extending out to 20A°.

The tracings were measured by an analogue-to-digital converter and then processed by computer for conversion to intensity. The reduction program was developed by J. E. Ross (unpub.) at UCLA and has been applied elsewhere (e.g. Aller and Ross 1967, Leckrone 1970). The processing allows for (1) any non-uniformities perpendicular to the direction of dispersion, and (2) the wavelength dependence of the density-intensity relation (which is significant) by linearly interpolating between the two closest D-I curves on either side of the line in question. Given the uncertainties in the calibration, and in the placement of the continuum and background fog levels, the maximum error in the measured line profiles should be of the order of 3% of the continuum intensity.

2.1 Emission-Line Spectrum

Unrectified intensity tracings of the spectral region, $\lambda 4610$ - $\lambda 4720$ are shown in Figure 1. These traces confirm previous spectral classifications based on low-dispersion spectrograms. Two stars, HD 15570 and HD 210839, have very strong Of characteristics. Note that HD 15570 seems to show weak emission of CIII $\lambda 4647$, $\lambda 4650$-1 as well as NIII and HeII emission. The classification of HD 46223 as an Of star is less definite in that HeII $\lambda 4686$ is a strong absorption line. The other three stars studied are definitely O stars.

The presence of emission lines in the spectra of the Of stars implies that the region of formation of the lines has a low electron density, for if the electron density were high, collisions would bring these lines into LTE. That is to say, the emission lines imply a low <u>effective</u> gravity. They do not necessarily imply, however, a low surface gravity, $g = GM_*/R_*^2$ because other factors (e.g. radiation pressure, centrifugal force) may play a role in producing an extended, low-density atmosphere. Additional evidence must be brought in to identify the cause of the extended atmosphere.

The existence of a velocity gradient has been detected in some Of stars whose spectra show HeII λ4686 strongly in emission. The emission profile in such stars often shows an asymmetry or self-reversal displaced shortward from the center of symmetry. The HeII λ4686 profile in the spectrum of HD 210839 shows irregularities which are greater than the plate noise. Perhaps these irregularities are actually several self-absorption features. As supporting evidence for this interpretation, Figure 2 shows the profile of HeII λ4686 in the spectrum of HD 190429A (O5f), showing clear evidence of blue-shifted absorption. It should be noted that HD 190429A was observed earlier by Oke (1954), and at this time, it showed no evidence of a self-reversal. Hence, the acceleration of matter cannot be considered a steady phenomenon. The λ4686 profile in HD 15570 shows no evidence of a self-reversal, but it is asymmetric. It would be very desirable to find whether HD 15570 also develops indications of outgoing matter at certain times.

2.2 H and He Spectrum

Selection of lines for gravity indicators should emphasize those lines which are formed near the photosphere and should therefore give a reliable indication of the true gravity near the photosphere rather than the effective gravity in the extended layers of the atmosphere. The wings of the HI lines appear to be well suited for this purpose. LTE calculations based on modern line-broadening theories (Griem 1960, 1962, 1967) and realistic model atmospheres show that these lines are still sensitive to gravity even in hot stars (Heap 1970). For example, the predicted width of Hγ + HeII λ4340, at a residual intensity, I = .900, in Bradley and Morton's (1969) line-blanketed models of a 37,450° star changes from 1.8 A° when log g = 3.5 to 4.7 A° when log g = 4.0.

Selected HI, HeI and HeII line profiles of the six stars are shown in Figures 3 through 8. Examination of the HI profiles shows that Of stars have weaker Stark wings than O stars of the same spectral type. (Compare Figure 3 with 4, 5 with 6, 7 with 8). This point is quite important. The absorption spectrum of an Of star is not identical to that of an O star of the same spectral type. An Of star cannot be considered simply as an O star with a few emission lines added to its spectrum.

2.3 Spectra of Heavier Elements

Equivalent widths (W_λ) of all visible lines are listed in Table 2. These data show no obvious differences in the general appearance of the metallic-line spectrum between Of stars and O stars. A possible exception is HD 210839 whose spectrum shows numerous weak, relatively thin lines in the UV. Identification of these lines is difficult because most are blends and are hardly stronger than the noise. Additional spectra are needed to confirm their presence and to identify these lines.

A summary of the measured widths at half intensity is given in Table 3. The widths listed in this table are uncorrected for instrumental broadening, but such a correction does not significantly alter the values. The line widths are of particular interest in that the weak absorption lines give an indication of the velocity fields near the photosphere, while the emission lines presumably given an indication of the velocity fields somewhat further out. One remarkable feature in both the Of stars and the O stars is that the NIII emission lines are somewhat broader than the weak absorption lines. This feature is also evident from Oke's (1954) data. The spectrum of HD 54662 is the only one studied here to show NIII λ4097 essentially unblended with the wing of Hδ. This absorption line corresponds to the next transition below the NIII emission doublet at λ4634, -40. Although a moderately strong line, it is still thinner than either of the emission lines.

Taken together, the widths of the absorption lines and the emission lines are consistent with the hypothesis of radial acceleration of material. This hypothesis has been suggested by Hutchings (1968, 1970a) on the basis of visual spectroscopic data, by Morton (1967), Morton, Jenkins and Brooks (1969), Stecher (1970) and others on the basis of UV spectroscopic data. The rocket spectra indicate that Of stars and O giants are losing mass at high velocities. It would be extremely interesting to know whether this holds true for early O stars as well.

2.4 Discussion

The most significant difference in the spectroscopic properties of Of stars and O stars is the difference in the hydrogen line profiles. The wings of the Balmer lines are much weaker in the Of stars than in the O stars. One interpretation of this difference is that Of stars have lower surface gravities than do O stars. This interpretation, as noted before, is consistent with calculations which show that these lines are still sensitive to Stark broadening even at high temperatures.

Another interpretation suggested by Underhill (1967) is that an Of star has an ordinary O-type atmosphere which is surrounded by a shell whose emission weakens the Balmer series of hydrogen, i.e. Of stars are the O-type counterpart to Be stars. This interpretation needs some clarification because the meaning of the term, "shell star," is ambiguous. The term often connotes a star surrounded by an envelope which is concentrated toward the equatorial plane of the star, and which is supported by centrifugal forces. A few stars like HD 155806 (Buscombe 1970) or γ Cas (Hutchings 1970b) seem to be O-type counterparts to Be stars. A case could even be made that HD 210839 is a shell star in this sense. The profiles of the hydrogen absorption lines and the Of-type emission lines indicate a (possibly rotational) velocity of the order of 400 km/sec, while the widths of the nitrogen and oxygen absorption lines in the UV, if real, are of the order of only 100 to 150 km/sec, so the latter lines could be interpreted as "shell lines." In addition, the irregularity of the emission profile of He II λ4686 could possibly be caused by absorption by shells moving at different velocities. Underhill (1958, 1959) has suggested that HD 188001 (O8f) is a shell star, but the same observational uncertainties hinder this interpretation as encountered here with HD 210839. In addition, the low rotational velocity

(110 km/sec) of HD 188001 (Slettebak 1956) would seem to rule out shell formation by rotational ejection of matter. The other two Of stars studied here have line widths corresponding to only 150 km/sec, and neither shows evidence of thin "shell lines." In a more extensive survey, Slettebak (1956) has shown that the widths of absorption lines of Of stars indicate velocities of the order of 150 km/sec and that about one-half of the measured broadening should be attributed to large-scale motions such as turbulence or convection rather than to rotation. Hence, observational evidence suggests that Of stars, in general, are not shell stars in the sense of being hotter counterparts to Be or B-shell stars.

In a less restrictive sense, the term "shell star" conveys the idea that a significant fraction of the line radiation originates in regions far outside the photosphere, and the mechanism of support of these outer atmospheric layers is left unspecified. In this sense, any star which has an extended atmosphere could be considered a shell star. The interpretation of an Of star as a shell star would still be consistent with the interpretation of an Of star as a low-gravity object, since a low-gravity star would presumably have an extended atmosphere whose radiation would lead to emission edges and emission lines in the visible region of the spectrum. Referring again to Figures 3 through 8, we note that the cores of the HI lines in the spectra of the Of stars are not so deep as those in the O stars, and it is possible that the HI lines in the Of stars are partially filled in by emission from an envelope, but conclusive proof of shell emission would require a demonstration that other factors are not involved in producing the shallow lines.

The case for shell emission becomes stronger when one considers the fact that a shell surrounding an Of star is not expected to be static. Motions on the order of 1500 km/sec have been observed in the rocket-UV spectrum of ζ Puppis, an O5f star (Morton et al 1969). At the wavelength of $H\gamma$, such motions would affect the observed line profile up to ± 20 A° from the line center. Hence, if a star has a shell whose radiation includes H recombination lines, the radiation of the shell in those lines should affect the whole absorption profile of a Balmer line. This effect in fact, has been observed in one star studied here, HD 46223. The HI lines are weak, and very broad emission wings are present, especially at the lower members of the series. Figure 9 shows the complete profile of $H\gamma$ in the spectrum of HD 46223. HD 15570 shows no evidence of emission wings. A case could also be made for broad emission wings flanking the HI lines in the spectra of HD 210839, but additional spectra are needed to confirm their presence. The lack of pronounced Stark-broadened wings in the spectrum of HD 46223 and HD 210839 may result from overlying shell emission, as well as low gravity.

This emission, as far as is known, is the first detection of extreme mass motions from an examination of the visual absorption spectrum of Of stars. However, it has been known for some time that the emission lines of some Of stars indicate extreme mass motions, when the profiles of these lines are examined at high dispersion (Wilson 1955, 1957).

3. PHOTOMETRIC COMPARISONS

The low gravities of Of stars indicated by their spectroscopic properties suggest that they are evolved objects and should therefore be more luminous then O stars of the same mass. Unfortunately, photometric detection of Of stars would be an impossible task at the present time. Evolutionary calculations by Stothers (1963, 1964) show that a 30 $M_\odot$ star brightens by only about one magnitude, during its course of evolution while still in the O-star stage. This difference in luminosity would be partially obscured by the range in masses among O stars. For example, Stother's 60 $M_\odot$ main-sequence model is brighter than any of the 30 $M_\odot$ models, even those representing the O-giant stage of a star.

In order to check the assertion that Of stars are evolved objects, all Of stars known to belong to clusters were investigated to see if, on the average, they were more luminous than O stars. To date, there are at least nine OB associations containing one or more Of stars for which UBV photometric data are available (cf. Table 4). In some cases, it is possible to find the distance to the association and the absolute magnitudes of the stars in the cluster. In these cases, it is possible to show (Figure 10) that Of stars have absolute visual magnitudes in the range, M_V = -5.5 to -7.5. Not all O giants are Of stars, but at least the majority of O giants are Of stars, and all Of stars are O giants in the sense that they are at least as bright as any O5 star.

The O9I stars provide further evidence supporting the interpretation of Of stars as high-luminosity objects in that O9I stars also show NIII in emission (Wilson 1957). These observations suggest that Of stars may be hotter counterparts of O9 supergiants.

Of the stars studied here, two pairs of stars belong to the same clusters, so they are useful in contrasting the luminosities of O and Of stars (cf. Table 1). HD 15570 (O5f) and HD 15629 (O5) both belong to Per OB1, and the Of star is the brighter of the pair, as expected. On the other hand, HD 46223 (O6f) and HD 46150 (O5), which belong to Mon OB 2, have the same absolute visual magnitude. Perhaps the equality in brightness is due to the larger mass of HD 46150.

4. RELATION OF SPECTRAL TYPE TO TEMPERATURE

The results of the preceding two sections show that an Of star and an O star of the same spectral type differ in two respects. First, an Of star, on the average, is more luminous than an O star of the same spectral type. Secondly, the absorption lines in the spectrum of an Of star are weaker than those in an O star of the same spectral type. These differences are apparent from an examination of the profiles shown in Figures 3 through 8. They are also detectable from equivalent width data given by Oke (1954), Underhill (1951), Mannino and Humblet (1955) and others. Most likely the cause of these differences is due to a difference in gravity between O and Of stars.

If this is the case, then it is necessary to reevaluate the meaning of spectral type when applied to O and Of stars together. Certainly among O stars having the same gravity, spectral type is an indicator of effective temperature. Indeed, Peterson and Scholz (1971) have shown that among O stars (as distinct from Of stars), spectral type has a one-to-one correlation with effective temperature as determined from ionization equilibrium of the heavier elements. The actual values of their T_e scales must be considered tentative however, since they depend strongly on the assumption of LTE, an assumption which is demonstrably inapplicable to the atmospheric region of continuum and weak line formation (Mihalas and Auer 1970). On the other hand, spectral type does not necessarily have a one-to-one correspondence with effective temperature when O and Of stars are considered together. Here it is necessary to find out to what extent gravity as well as temperature determines spectral type.

One approach to the problem of estimating the relative importance of temperature and gravity on spectral type is to synthesize line spectra from models having the same temperature but different gravities and then to find whether they would yield the same spectral type. This approach must await a detailed calculation of the line spectrum which takes into account non-LTE effects. In the meantime, it seems doubtful that stars having the same temperature but different gravities would have the same spectral type. As mentioned earlier, spectral type is estimated from the equivalent width ratios W(HI)/W(HeII) and W(HeI)/W(HeII). The results of the preceding sections would disqualify the ratio, W(HI)/W(HeII), as an indicator of temperature on the grounds that this ratio is demonstrably sensitive to luminosity and gravity. This argument has been advanced previously by Botto and Hack (1962) and Hack (1963). Hack therefore used only the ratio, W(HeI)/W(HeII), to estimate spectral type. This ratio, however, may also be dependent on gravity. If two stars have the same temperature but different gravities, they will not necessarily have the same W(HeI)/W(HeII) ratio because (1) the ratio of the number of ionized to netral helium atoms is dependent on electron pressure and, hence, gravity, and (2) the ability of HeI or HeII atoms to absorb radiation over a wide wavelength interval is dependent on gravity (since Stark broadening is dependent on electron pressure), and (3) deviations from LTE strengths are most probably sensitive to gravity. It seems very unlikely that these effects of a change in gravity would cancel and preserve the ratio W(HeI)/W(HeII).

An alternative approach to estimating the relative effects of temperature and gravity on spectral type is to find whether O and Of stars share the same relation of spectral type to temperature. If Of stars and O stars of the same spectral type have different temperatures, this difference would be evidence that gravity plays an important role in determing spectral type. In order to make such a comparison, one needs estimates of temperatures that are found without reference to the line spectrum. At present, there are three different measurements of continuous flux, which are used to derive effective temperature. The three temperatures are: the Lyman continuum temperature (T_Z) derived by Morton (1969) using a method similar to the Zanstra method; the UV continuum temperature derived by Smith (1967) from measurements of ($m_{1376Å}-m_V$) corrected for interstellar reddening; and finally, the continuum temperature (T_{BaD}) derived by Morton and Adams (1968) from measurements of the Balmer discontinuity made by Chalonge and Divan (1952).

Those O and Of stars whose temperatures were derived from observations of their continuous flux and which form the basis of recent temperature scales are listed in Table 5 according to spectral type. Successive columns list the identification number of the star, spectral type, and the three continuum effective temperatures, T_{UV}, T_Z, T_{BaD}, as published.

The BaD temperature scale is open to two criticisms. First, Mihalas and Auer's (1970) non-LTE calculations show that the Balmer discontinuity does not die out at high temperatures as quickly as previously assumed from LTE calculations. They therefore suggest that the T_{BaD} temperature scale should be revised upwards to account for the smallness of the observed Balmer jump in early O stars. Secondly, the Balmer jump may possibly be diminished by shell emission in Of stars. Cassinelli's (1970) extended atmosphere model of a 37,496° star, whose atmospheric extent is roughly equal to the radius of curvature, shows an <u>emission</u> edge at the Balmer discontinuity. Hence a small Balmer jump could either indicate an extended atmosphere or high temperature. For these reasons, comparison of the T_{BaD}'s of Of stars and O stars of the same spectral type does not seem a proper way to answer the question whether Of stars and O stars share the same spectral type-temperature relation.

Unfortunately, there are only three Of stars whose continuum effective temperatures have been determined by other means: BD + 60°2522, HD 210839, and HD 66811. Both HD 210839 (O6f) and BD + 60°2522 (O7f) have a T_Z = 34,000°K. This value is near the mean T_Z for O7 stars but considerably lower than the mean for O6 stars. HD 66811 = ζ Pup (O5f) has a $T_{uv} = 31{,}000°$, which is confirmed by Aller, Faulkner, and Norton's (1966) spectrophotometry in the visual region. This value is given high weight in view of the recent direct determination of effective temperature for this star. Davis, Morton, Allen, and Hanbury-Brown (1970) deduced the same value for its effective temperature from measurements of its angular diameter. It therefore seems reasonable to interpret the low effective temperature of ζ Puppis as an indication that an O5f star could very well be cooler than an O5 star, and hence, that spectral type is not simply a function of temperature but also of gravity.

5. SUMMARY AND CONCLUSIONS

In summary, both spectroscopic and photometric data indicate a measurable intrinsic spread in gravity among O stars in general, and they give evidence that the presence of emission lines typical of Of stars is a consequence of low gravity. If this interpretation is correct, then O and Of stars should not be placed together in one sequence of spectral type vs. temperature without proof that the same sequence applies to both types of stars. Instead, the effect of gravity on the line spectrum should be taken into account.

Non-LTE calculations are needed to show whether the HeII line spectrum of low-gravity stars peaks in strength at temperatures lower than those appropriate to high-gravity stars. In addition, there is a strong need for a few stars to be studied in detail (especially those belonging to clusters of well-known distances) and their temperatures derived by several different methods. Only when the effective temperatures of these few stars are firmly established, should they be arranged in a sequence of temperature and gravity, their line spectra studied for trends that are easily visible, and new spectral sequences for O and Of stars established.

Since any temperature determination of an O or Of star requires a comparison of the observed line flux or continuous flux with that predicted from a model atmosphere, it is important the assumptions behind the model are correct. Hopefully, the observations presented here will be useful tests for present and future models of O and Of stars. Most models of O and Of stars assume a plane-parallel atmosphere which is in radiative and hydrostatic equilibrium. Spectroscopic observations, however, presented in Part 2 suggest that spherical and hydrodynamic effects may be important.

This study was included as part of a Ph.D. thesis under the guidance of Dr. L. H. Aller on a related topic (the spectra of central stars of planetary nebulae), which was submitted to the University of California at Los Angeles. I would like to thank Dr. Aller and Dr. Edward Upton for advice and encouragement. I would also like to thank Drs. D. M. Popper and H. W. Epps for obtaining the spectrograms of the stars shown here.

TABLE 1. Data Pertaining to Stars Observed

HD	Spectral Type	$V^{(1)}$	Association[2]	$M_v^{(3)}$	$v^{*(4)}$ (km/sec)	Previous Studies[5]
15570	05f	8.10	Per OB1	-6.5		Un
15629	05	8.42	Per OB1	-6.0		Un
46223	06f or 04	7.28	Mon OB2	-7.2	110	Un, Sl
46150	05	6.76	Mon OB2	-7.2	110	Un, Ok, Sl
210839	06f	5.05			150:	Un, BH
54662	06	6.20			≤75	Un

References and Notes

(1) Hiltner and Johnson (1956), Johnson and Morgan (1953), Wildey (1964)

(2) Ruprecht (1964)

(3) Values of M_v are based on individual reddening corrections and distance determination by the "cluster parallax" method.

(4) Slettebak (1956).

(5) Un = Underhill (1951), Ok = Oke (1954), Sl = Slettebak (1956), BH = Botto and Hack (1962).

TABLE 2

Equivalent Width Measurements in the Spectral Region, λ4686-λ3700

λ	ID	HD 46223	HD 46150	HD 15629	HD 15570	HD 210839[1]	HD 54662
4686	HeII	.62	.63	.64	3.46E	1.14E	.90
4647-58	CIII,CIV				1.42E		
4640	NIII	.42E	.22E	.17E	.89E		.17E
						1.03E	
4634	NIII	.23E	.16E	.12E	.54E		.12E
4542	HeII	.65	.65	.77	.57	.62	.72
4471	HeI	.17	.32	.21		.38	.44
4340	H_γ+HeII	1.48	1.88	1.85	1.45	1.53	2.16
4227	NII					.12	
4200	HeII	.50	.61	.73	.42	.72	.74
4116	SiIV				.31E		
4101	H_δ+HeII	1.84	1.88	1.88	1.25	2.12	2.15
4088	SiIV				.23E		.20
4067	CIII						.33
4026	HeI+HeII	.39	.53	.20	.26	.56	.40
3970	H7+HeII	2.38	1.59	2.04	1.26	2.18	1.66
3961	OIII				.17		
3923	HeII	.54	.21	.48	.29	.46	.31
3889	H8+HeII	2.46	1.88	1.75	1.29	1.40	1.91
3858	HeII	.34		.31		.49	
3835	H9+HeII	1.80	1.64	1.69	.84	1.55	1.44
3819	HeI			.12		.33	.26
3813	HeII		.21	.25		blend	
3797	H10+HeII	1.45	1.06	1.28	1.29	1.19	1.19
3791	OIII	.08	.14	.16	.20		.14
3774	OIII,OIV	.08					
3770	H11	.86	1.02	.94	.84	.86	.86
3759	OIII	.24	.16	.23		.46	.24
3757	OIII	.09	.14	.18			.18
3754	OIII,NIII	.19	.15	.36			
3750	H12	.96	.67	.84	.78	.90	
3745	OIV			.13			
3734	H13	.77	.60	.69	.74	1.01	.46
3729	OII,OIV			.16		.09	
3725	OII,OIV			.16		.06	
3721	H14	.64	.54	.46	.81	.61	.31
3711	H15	.42	.34	.35	.50		
3704	H16		.25	.32			

[1] This star has numerous, blended O and N lines in the UV, which are not listed here.

Table 3. Measured Half-Widths Expressed in km/sec.

HD	Spectral Type	Emission Lines HeII (Km/sec)	Emission Lines NIII (km/sec)	Absorption Lines Si IV (km/sec)	Absorption Lines OIII (km/sec)	Absorption Lines NIII (km/sec)	Absorption Lines NIV (km/sec)
15570	05f	590	190	170:E	170	nm*	tf*
15629	05		120	np*	110:	nm	150
46223	06f?		190	np	110	nm	130
46150	06		250	np	110	nm	150
210839	06f	610	>400	np	nm?	nm	tf
54662	06		240	110A	110	140	tf
Lines Used:		λ4686	λ4634 λ4640	λ4088 λ4116	λ3754 -57 -59 -74	λ4097	λ3478 -82 -84

*Notes: nm = not measurable, due to blending
np = not present
tf = spectrum too faint for measurement

TABLE 4. Associations Containing Of Stars

Association (Ruprecht 1964)	Of Stars HD	Sp. Type	M_v	Assumed $V_o - M_v$	Primary References
Cas OB5	108	O8f	See Figure 10	11.95	Ruprecht (1964) Hiltner (1956)
Per OB1	14947 15570 16691 17603	O6f O5f O5f O7f:	See Figure 10	12.00	Wildey (1964)
Mon OB2	46223[1]	O6f:	-7.2	12.35	Johnson & Morgan (1953) Hiltner & Johnson (1956)
η Car Complex	93403[2]	O5f:	-5.5	12.00	Faulkner (1963)
Sco OB1	151804 152408 152248	O8fp O8fp O8f	See Figure 10	11.30[3]	Bok, Bok, and Graham (1966)
Ser OB1	167971	O8f	See Figure 10	11.50	Morgan *et al.* (1953) Hiltner (1956)
Cyg OB1	192639 193514	O8f O7f	See Figure 10	11.15	Roman (1951) Morgan *et al.* (1953) Hiltner (1956)

Continued

TABLE 4. Associations Containing Of Stars

Association (Ruprecht 1964)	Of Stars HD	Sp. Type	M_v	Assumed $V_o - M_v$	Primary References
Cyg OB2	MM5	O7f	-7.1 (ec. bin.)	10.90	Johnson & Morgan (1953)
	MM7	O6f	-5.7		Schulte (1958)
	MM8A	O6f	-6.8		
	MM9	O5f	-6.9		
	MM11	O6f	-6.1		
Cyg OB3	190429A[4]	O5f		11.80	Roman (1951)
	190864 [5]	O5.5f:			Morgan et al. (1953)
					Hiltner (1956)

Notes:

(1) HD 46223: Classification as an Of star is uncertain. (Underhill 1951, Morgan et al. 1965)

(2) HD 93403: Membership in cluster and distance is uncertain.

(3) Schild, Hilter, and Sanduleak (1969) obtained $V_o - M_v = 11.5$.

(4) HD 190429A: No UBV photometry exists for this star alone.

(5) HD 190864: Classification as an Of star uncertain (Underhill 1951, Morgan et al. 1954).

TABLE 5. Comparison of Continuum Effective Temperatures

HD, BD	Spectral Type	T_z[(1)] (10^3 °K)		T_{uv}[(2)] (10^3 °K)	T_{BaD}[(3)] (10^3 °K)	
		Hα	Radio-ν		$g=10^{3.5}$	$g=10^{4.0}$
-16^o4826	05	57	95			
164794[(4)]	05	50	42			
66811	05f			31		
199579[(4)]	06	52	53			
152723	06	..	43			
206267[(4)]	06n	41	34		31	35
37022[(5)]	06	38	37		34	40?
5005	06	38	36			
42088	06	37	40			
215835[(4)]	06		36			
210839	06f	34			31	35
$+22^o3782$	07		45			
164492	07	39	39			
227018	07		36			
47839	07	34		29		
203064	07				30	33
24912	07	30	30	40	29	33
$+60^o2522$	07f	34	34			
36861	08	36				

References and Notes:

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3. Morton and Adams (1968), Bradley and Morton (1969), Chalonge and Divan (1952). Estimates of temperature are given for two different values of gravity (g).

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Captions to Figures

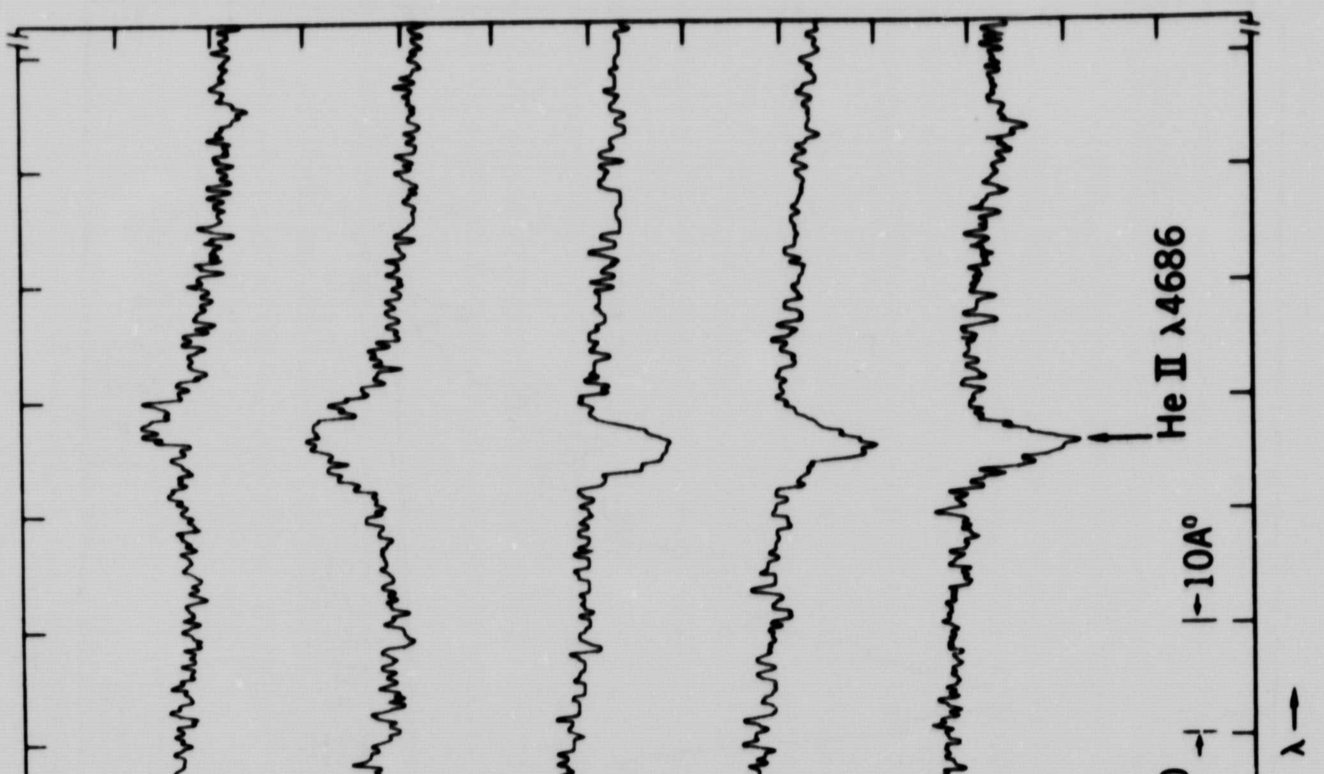
Figure 1. Unrectified Intensity Tracings of the Spectral Region, $\lambda 4610$-$\lambda 4720$. Marks along the vertical axis are given every 0.2 of the continuous intensity at $\lambda 4686$.

Figure 2. Unrectified Profile of HeII $\lambda 4686$ in HD 190429A. This profile was reduced from a 46 A°/mm spectrogram obtained by H.W. Epps at the Ojai Observatory of the University of California at Los Angeles. The displaced absorption feature is clearly visible on the plate.

Figures 3 through 8. Intensity Profiles of Selected HI, HeI, HeII Lines. Marks along the vertical axis are given every 0.1 of the continuous intensity at the line center.

Figure 9. Complete Intensity Profile of $H\gamma$ in the Spectrum of HD 46223. The profile was taken from a density tracing and an approximate intensity scale superposed. The solid line shows the level of the continuum.

Figure 10. Composite M_V - Spectral type Diagram.



HD 210839
HD 15570
HD 46223
HD 46150
HD 54662
N III λ4634
N III λ4640
He II λ4686
10A°
0.2
I
λ

Figure 1

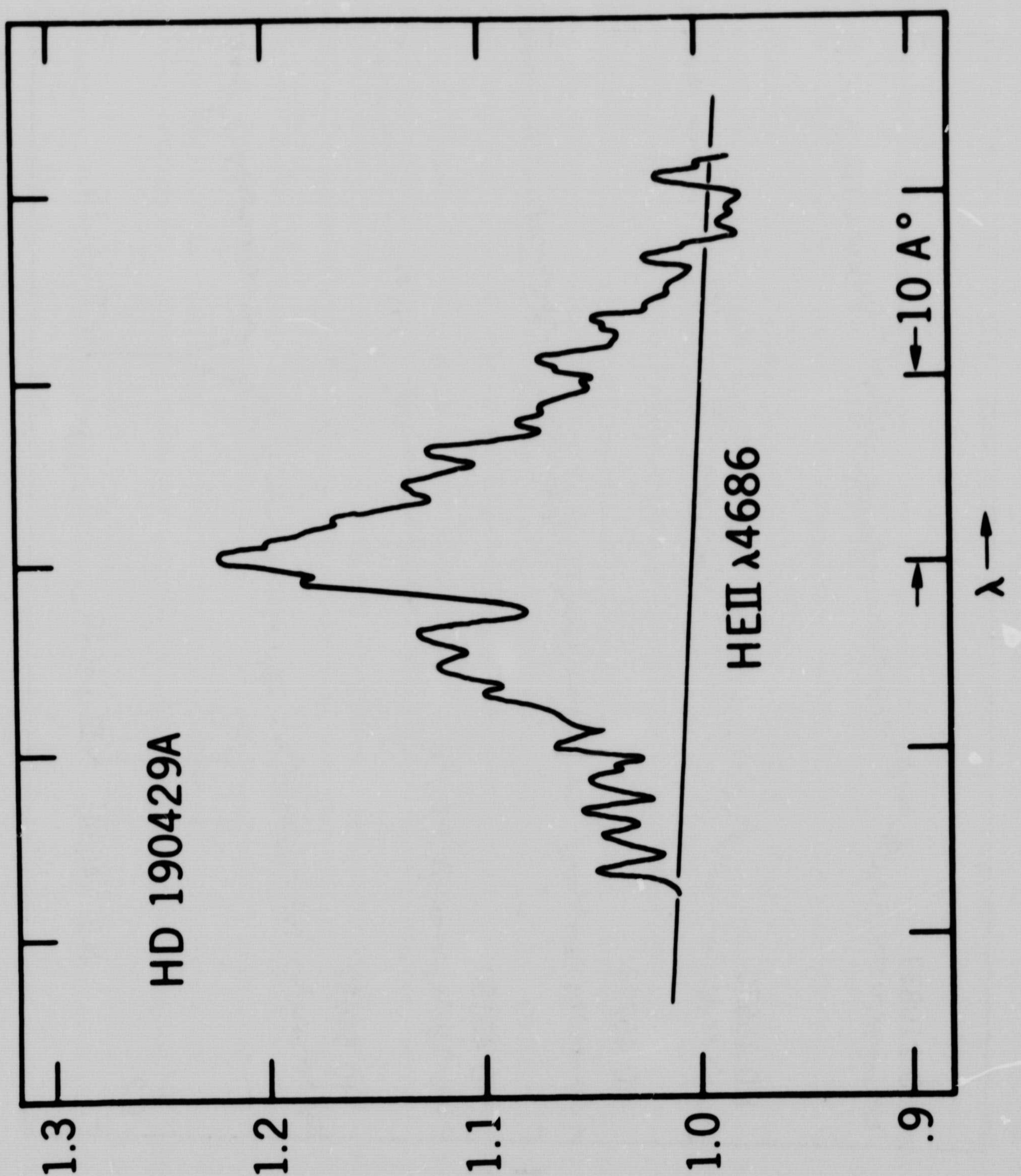
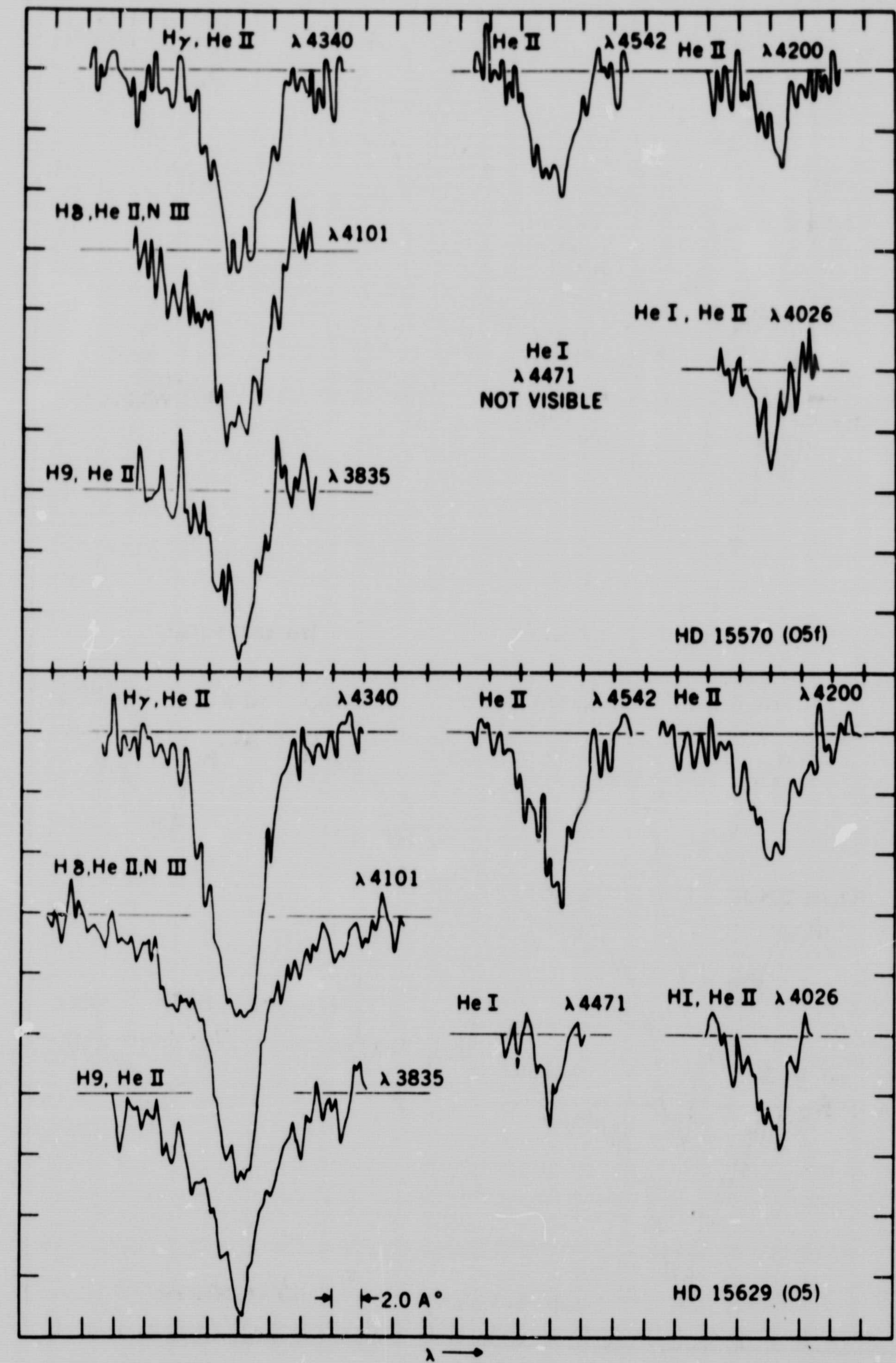
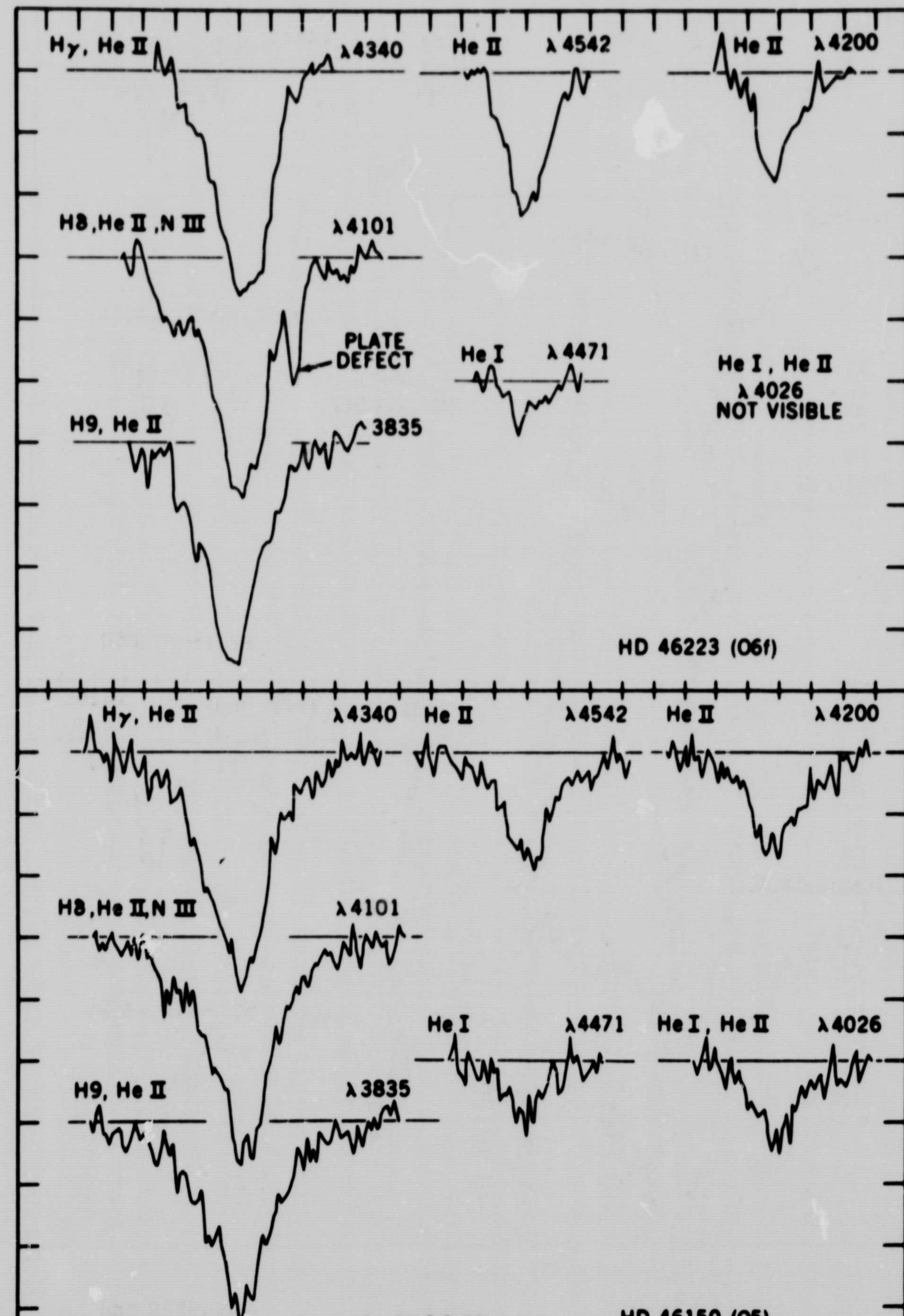


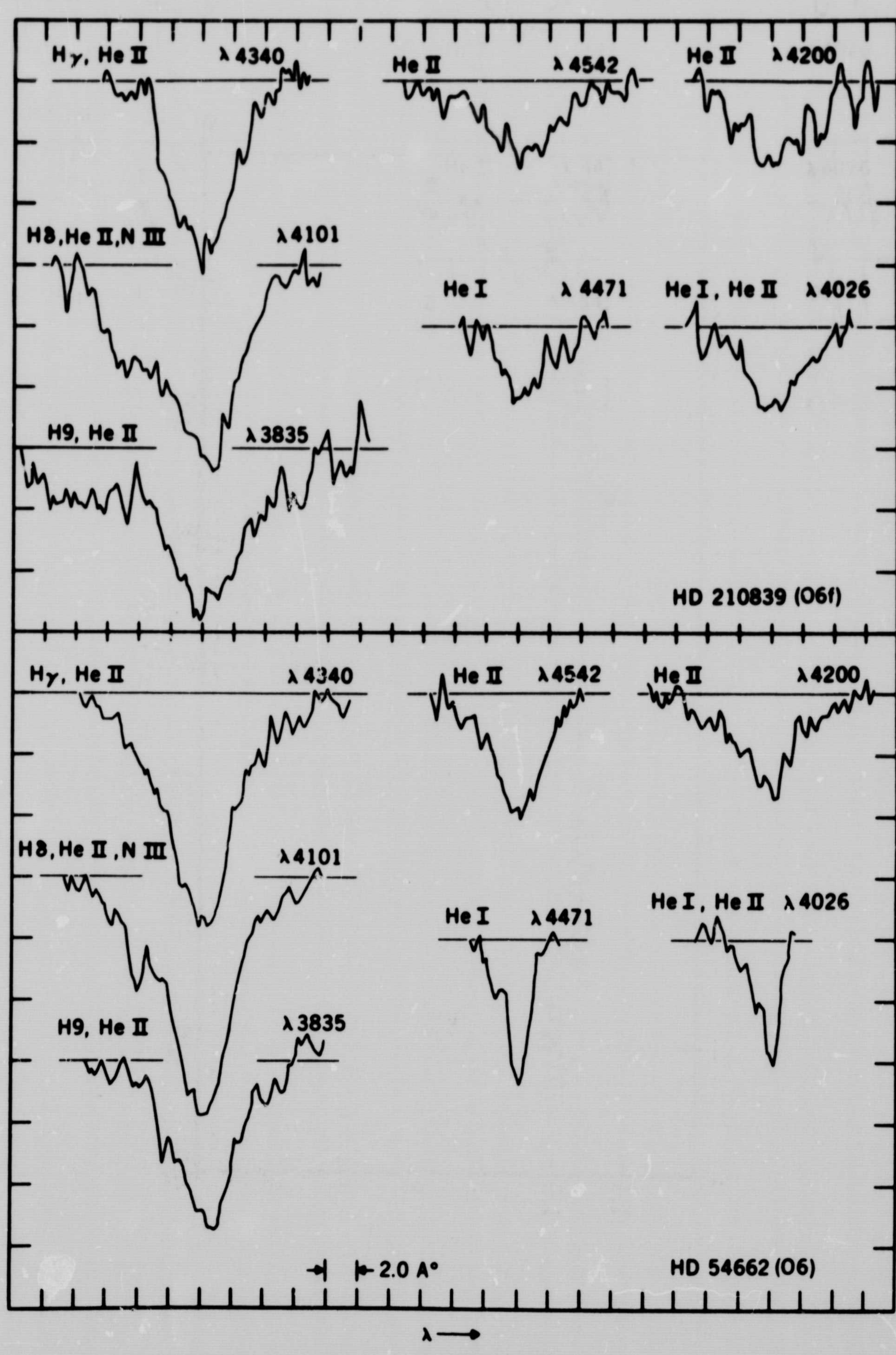
Figure 2



Figures 3 and 4



Figures 5 and 6



Figures 7 and 8

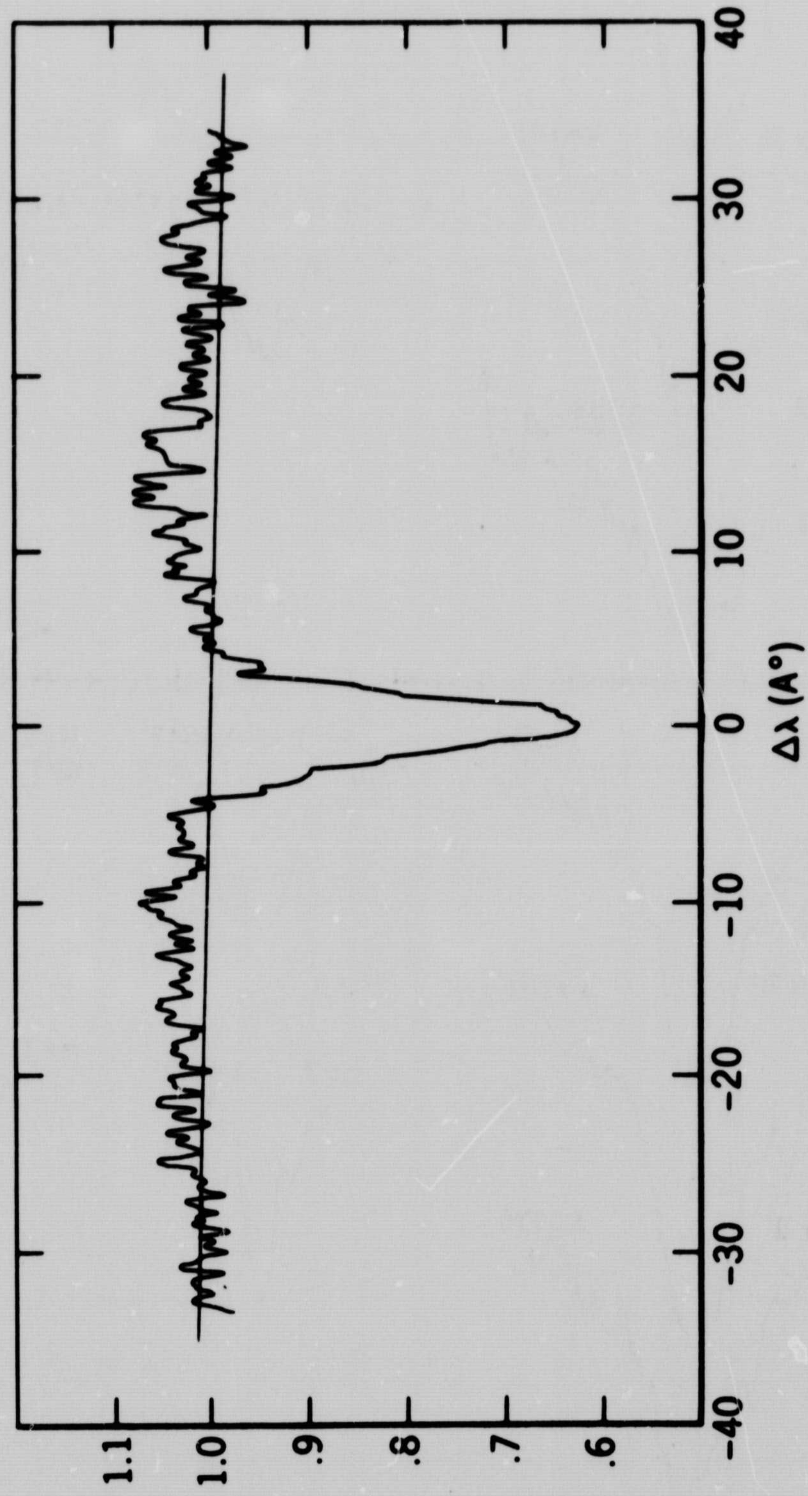


Figure 9

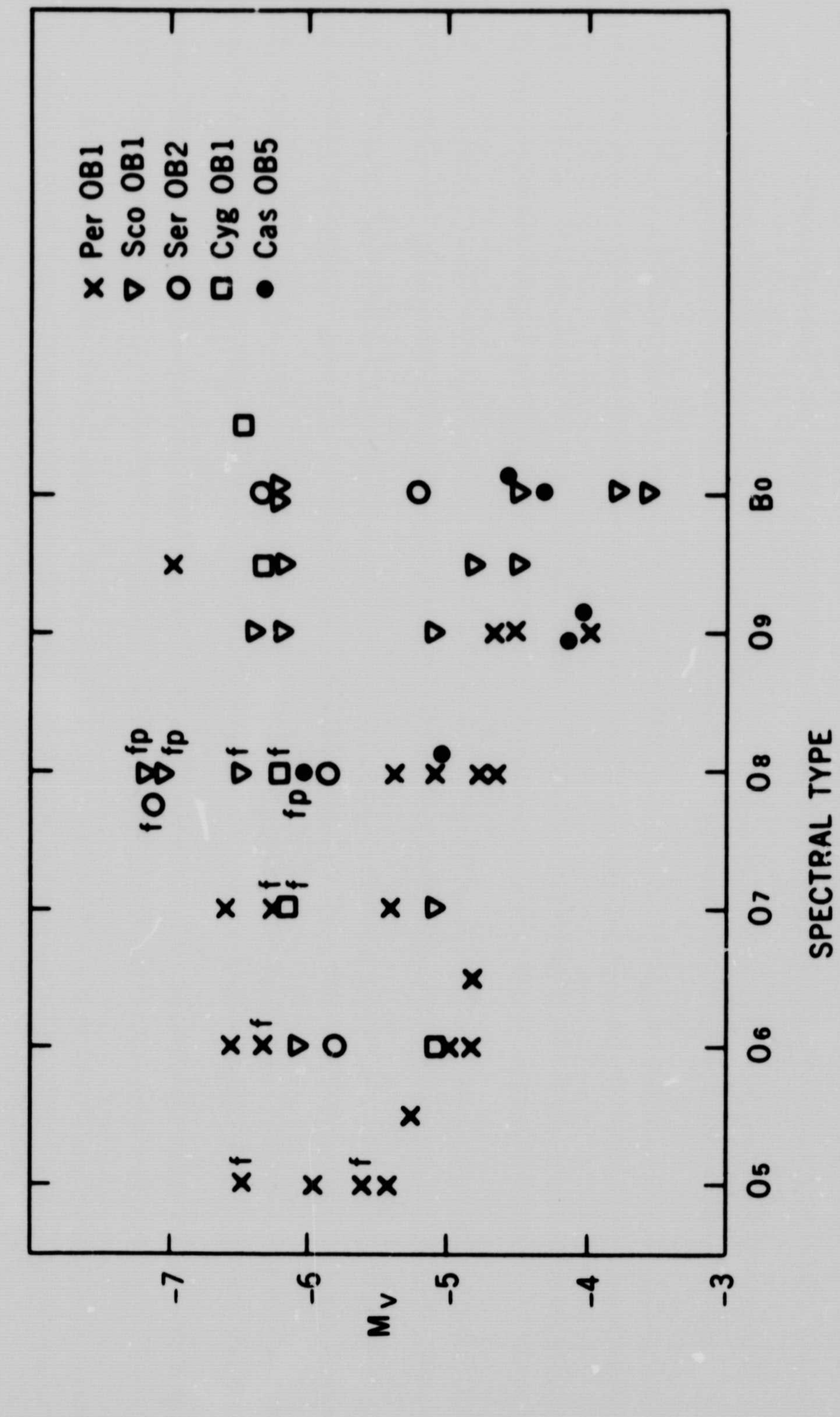

Per OB1
Sco OB1
Ser OB2
Cyg OB1
Cas OB5
SPECTRAL TYPE
O5
O6
O7
O8
O9
B0
Mv
-7
-6
-5
-4
-3

Figure 10