ANOMALOUS IONIZATION SEEN IN THE SPECTRA OF B SUPERGIANTS

Joseph P. Cassinelli and David C. Abbott

Washburn Observatory
Madison, WI 53706

ABSTRACT

An IUE survey of B supergiants has been conducted to study the persistence with spectral type of the ultraviolet resonance lines of N V, C IV, and Si IV. N V is seen as late as B2.5Ia, C IV until B6Ia and Si IV throughout the range from B1.5 to B9. This is in fairly good agreement with the Auger ionization model of Cassinelli and Olson (1979). The terminal velocities are derived for the 20 stars in the sample and it is found that the ratio v_T/v_{esc} decreases monotonically with spectral type from the value of 3.0 that it has in the O spectral range to the value 1.0 at B9Ia.

INTRODUCTION

Unexpectedly high ionization stages such as O VI were seen in the Copernicus spectra of O stars (Snow and Morton, 1976). Several possible explanations were considered by Cassinelli, Lamers and Castor (1978). X-ray emission has now been discovered from O stars by observations from the Einstein satellite (Harnden et al. 1979, Seward et al. 1979, Long and White 1980), and it is now clear that there is some very hot gas in the outer atmospheres of the stars. The x-ray emission is sufficient to produce the ionization anamolies in the cool outflow by the Auger mechanism as had been proposed by Cassinelli and Olson (1979). In this process, a total of two electrons are ejected from C, N or O following the K shell absorption of an x-ray photon. (Weisheit 1974). Thus if the dominant stage of ionization in the outflow is O IV a trace amount ($\sim 10^{-3}$) of O VI is produced, which is sufficient to explain the P Cygni lines seen in the UV spectra. As O IV should be an abundant ion stage (>10%) for stars as late as B0.5Ia (Teff = 29000) O VI should persist to that spectral type and no further. Morton (1979) carried out a careful study of Copernicus spectra of early B supergiants and found that O VI does persist to B0.5 and is absent at B1Ia.

In a similar fashion N V should persist as long as N III is a dominant ion stage and C IV as long as C II is a dominant ion stage in the cool parts of the wind. To give further test of the Auger ionization model we have carried out a survey of 20 B supergiants in every spectral class from B1.5 to B9Ia.

OBSERVATIONAL RESULTS

Figure 1 shows the spectra at N V 1239, 1243Å for 11 of the B supergiants from B1.5 to B5. The line is clearly present from B1.5 to B2Ia but disappears at later spectral types. At the bottom of the array of spectra is shown the results of theoretical calculations of absorption line strengths expected in a 20,000 K star at $N_e = 10^{11}$ cm^{-3}. These were calculated using f values from Kurucz and Peytremann (1975) supplemented by more recent work by Abbott (1978), Morton (1978) and others. LTE populations were used in the calculation of the line strength, and the plotted line segments are proportional to the logarithm of the strength. After accounting for these background lines, we concluded that N V is present only as far as B2.5Ia where, using the calibration of Underhill et al. 1979, T_{eff} = 20400. As usual terminal velocities of the winds, v_T, can be derived for each line from the maximal shortward displacement of the absorption feature.

Figure 2 shows the spectra of all 20 supergiants in our survey in the region of the C IV doublet 1548, 1551Å. For the earlier stars the line displays the broad strong P Cygni profile familiar in O stellar spectra. The line becomes progressively weaker for the later spectral types. After consideration of the calculated strengths of the photospheric lines, we concluded that C IV in the wind could be traced as far as B6Ia at which the effective temperature is about 12000Å. In an earlier IUE survey Underhill (1979) noted the presence of C IV as late as B5Ia. The theoretical photospheric line strengths at the bottom of the figure were calculated as before, but now using 15000 K for the left panel and 10000 K for the right panel. Again terminal velocities are derived from each line.

Figure 3 shows the Si IV doublet 1394, 1403Å region of the spectrum. The line clearly persists beyond either N V or C IV and continues throughout the sequence to B9Ia. (If the wind were in radiative equilibrium and not subject to x-radiation it would disappear at B3Ia.)

The spectrum of θ Ara shows distinctive structures in the resonance lines of N V, C IV and Si IV. There is an apparent contribution from the lines at zero velocity displacement. This roughly symmetric contribution could perhaps have been produced in a "transition region" between the photosphere and x-ray forming region.

DISCUSSION

The run of "terminal" velocities, derived for the three ions, versus spectral type is shown in Figure 4. For Si IV the velocity is determined from the stronger component at 1393Å. Indicated in this Figure is the result that N V persists to B2.5Ia and C IV to B6Ia. These are in rather good agreement with what is expected if N V is produced from N III and C IV is produced from C II by the Auger mechanism. (Cassinelli and Olson 1979). The persistence of Si IV can also be explained by the Auger mechanism but as the ion Si II has more than 10 electrons the analysis is more complicated (Weisheit 1976). The ion could eject from 2 to 4 electrons following L or K shell absorption of x-radiation. In any case it is not surprising that it should persist to later spectral types than does C IV.

Also shown in Figure 4 is the escape speed at the photosphere versus spectral type. These were derived from the data on cluster membership distances, effective temperatures (Barlow and Cohen 1977) and masses derived from theoretical evolutionary tracks (Chiosi et al. 1978), in the manner described in the terminal velocity survey of Abbott (1978). In that paper Abbott derived the ratios of v_T/v_{esc} for 36 stars, all but one of spectral type B1 or earlier plus some Wolf Rayet stars. He found $v_T/v_{esc} = 3.0$. IUE spectra of other O-type stars also show a $v_T/v_{esc} = 3.0$ scaling (Garmany 1980). This relation does not hold for B supergiants as is seen from Figure 4. The terminal velocity decreases monotonically from $\sim 2.7\ v_{esc}$ at B1.5Ia to $1.0\ v_{esc}$ at B9Ia. The A2Ia star, α Cyg, also has $v_T = 1.0\ v_{esc}$.

Thus, there is a continuous relation between v_T and v_{esc} extending from the earliest O stars to the latest B supergiants. The reason for the decreasing value of v_T/v_{esc} in the later type stars is not clear. The effective temperature, gravity and rotational velocity are all properties which decrease monotonically from early O-stars to late B supergiants.

The decrease in v_T/v_{esc} does not conflict with the line driven wind theory of Castor, Abbott and Klein (1975). As discussed by Abbott (1978), that theory predicts $v_T = [\alpha/(1-\alpha)]^{1/2}\ v_{esc}$ where α is a numerical constant which is determined by the mixture of optically thick and optically thin lines. If all the lines are optically thick $\alpha=1$, and if all the lines are thin $\alpha=0.0$. In this model $\alpha = 0.9$ gives $v_T/v_{esc} = 3.0$, and $\alpha=0.5$ gives $v_T/v_{esc} = 1.0$. The result of Figure 4 therefore may indicate that the ionization balance changes in B supergiants from a radiation force dominated by a few very strong lines to a force produced from lines which are more numerous but weaker.

The x-ray emission of early type supergiants also changes in character at around B1.5Ia. Vaiana et al. (1980) notes that essentially every O star observed by Einstein is an x-ray source. However in the Einstein survey of O and B supergiants Cassinelli et al. (1980) have found that there is a change at B1.5. All objects at B1.5I and earlier were detected with $L_x \approx 10^{-7.5}\ L_{Bol}$ whereas limits on x-ray luminosities beyond B1.5Ia were lower than $10^{-8.0}\ L_{Bol}$. Thus there is reason for pursuing further studies of the anomalous ionization in B supergiants. It may be the best diagnostic for studying the coronae or hot flow instabilities now available.

REFERENCES

Abbott, D.C. 1978a, J. Phys. B: Atom. Molec. Phys. 11, 3479.
Abbott, D.C. 1978b, Ap.J., 225, 893.
Barlow, M.J., Cohen, M. 1977, Ap.J., 213, 737
Cassinelli, J.P., Castor, J.I., Lamers, H.J.G.L.M. 1978, P.A.S.P., 90, 496.
Cassinelli, J.P., and Olson, G.L. 1979, Ap.J., 229, 304.
Cassinelli, J.P., Waldron, W.L., Vaiana, G., Rosner, R. 1979, in prep.
Castor, J.I., Abbott, D.C. and Klein, R.I. 1975, Ap.J., 195, 157.
Chiosi, C., Nasi, E. and Sreenivasan, S.R. 1978, Astr. Ap., 63, 103.
Garmany, K. 1980, private comm.
Harnden, F.R., Branduardi, G., Elvis, M., Gorenstein, P., Grindlay, J., Pye, J.P., Rosner, R., Topka, K., and Viana, G.S. 1979, Ap.J. (Letters), 234, L51.
Kurucz, R.L., Peytremann, E. 1975, SAO Sp. Rpt. 362. Smithsonian Inst. Washington, D.C.
Lamers, H.J.G.L.M., Snow, T.P. 1978, Ap.J., 219, 504.
Long, K.S. and White, R.L. 1980, Columbia Astro. Lab. Contribution No. 183.
Morton, D.C. 1978, Ap.J., 222, 863.

Morton, D.C. 1979, M.N.R.A.S., 189, 57.
Snow, T.P. and Morton, D.C. 1976, Ap.J. Suppl., 32, 429.
Seward, F.D., Forman, W.R., Giacconi, R., Griffiths, R.E., Harnden, F.R., Jones, C. and Pye, J.P. 1979, Ap.J., 234, L51.
Underhill, A.B. 1980, Ap.J., 235, 149.
Underhill, A.B., Divan, L., Prevot-Burnichan, M.L. and Doazan, V. 1979, M.N.R.A.S., 189.
Vaiana, G. et al. 1980, submitted to Ap.J.
Weisheit, J.C. 1974, Ap.J., 190, 735.

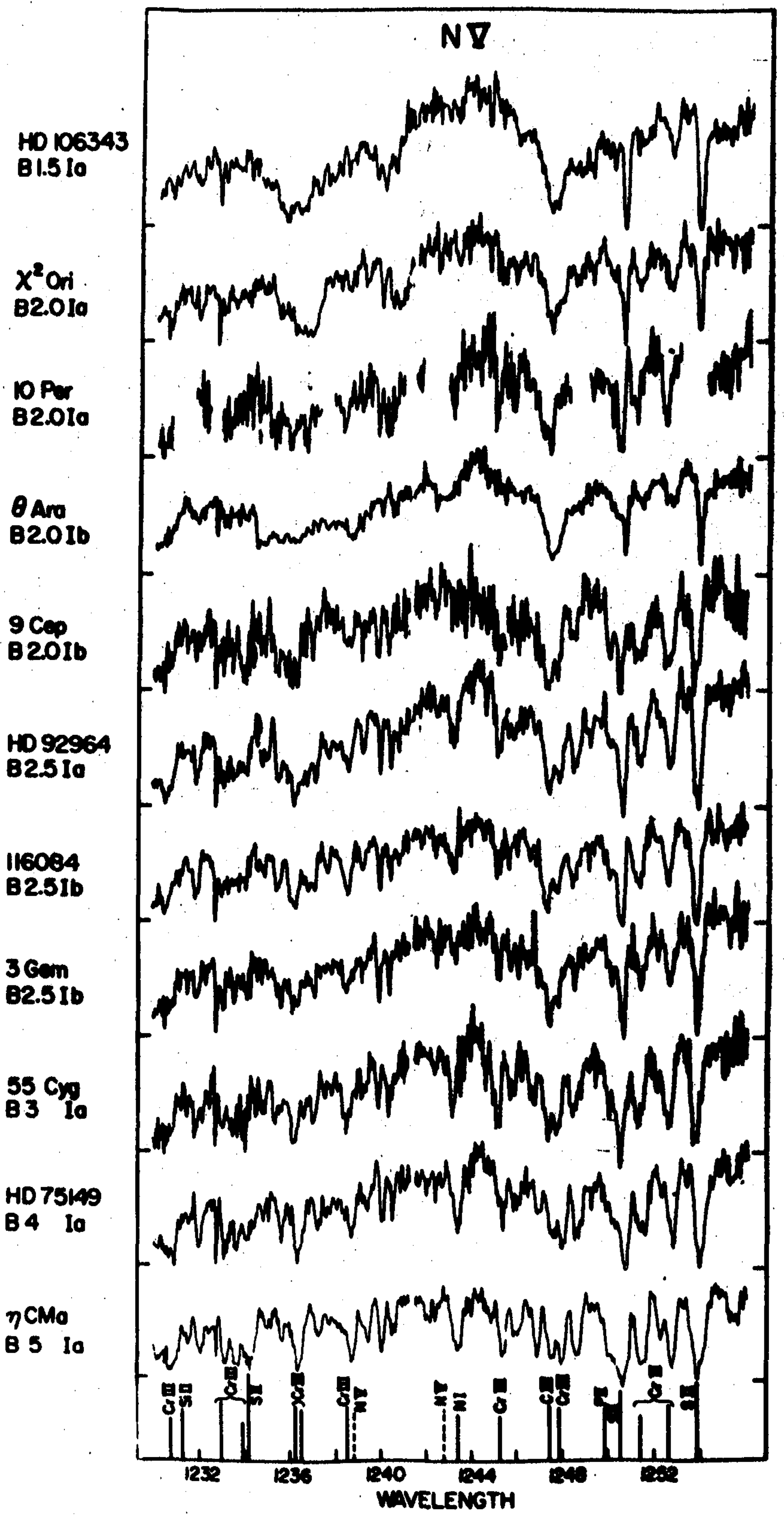

Fig. 1: The spectral region near 1240Å in B supergiants from B1.5 to B5. The major photospheric and interstellar lines in the region are identified at the bottom. The predicted relative strength of these spectral lines is indicated by the length of the line segment. Lines whose opacity was not calculated (usually interstellar) are indicated by dashed lines.

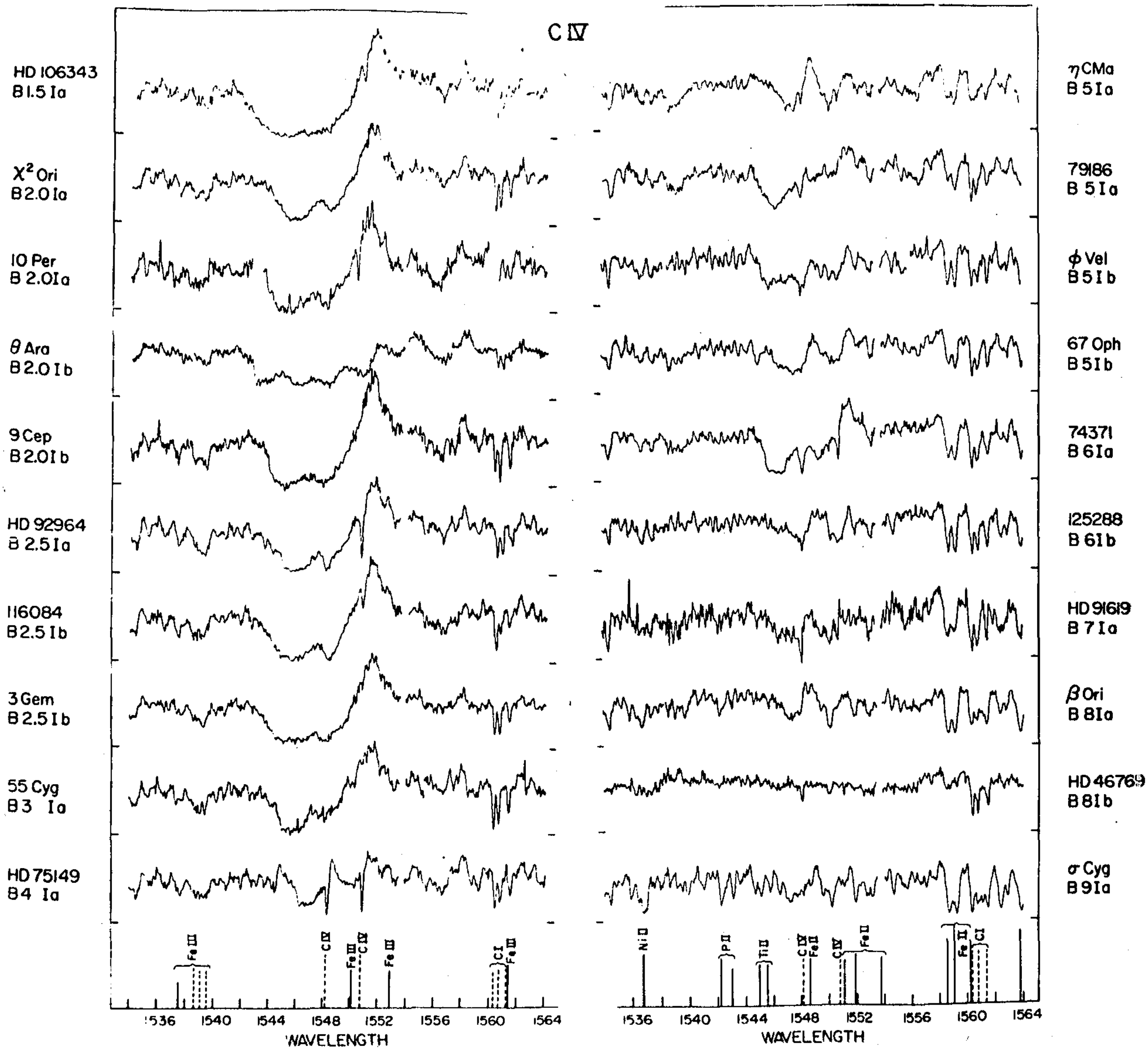

Fig. 2: The spectral region near 1550Å in B supergiants from B1.5 to B9.

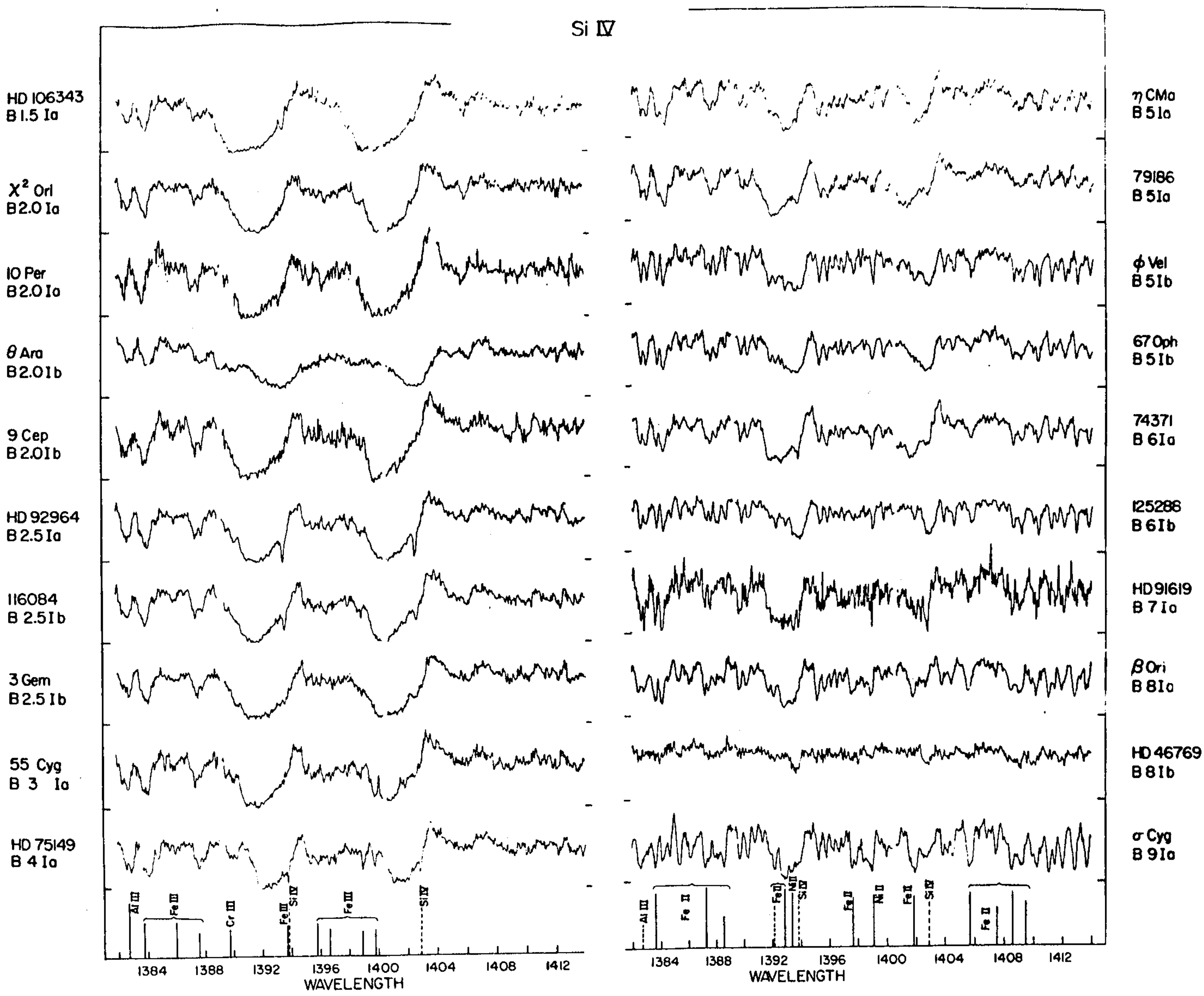

Fig. 3: The spectral region near 1400Å for B supergiants from B1.5 to B9.

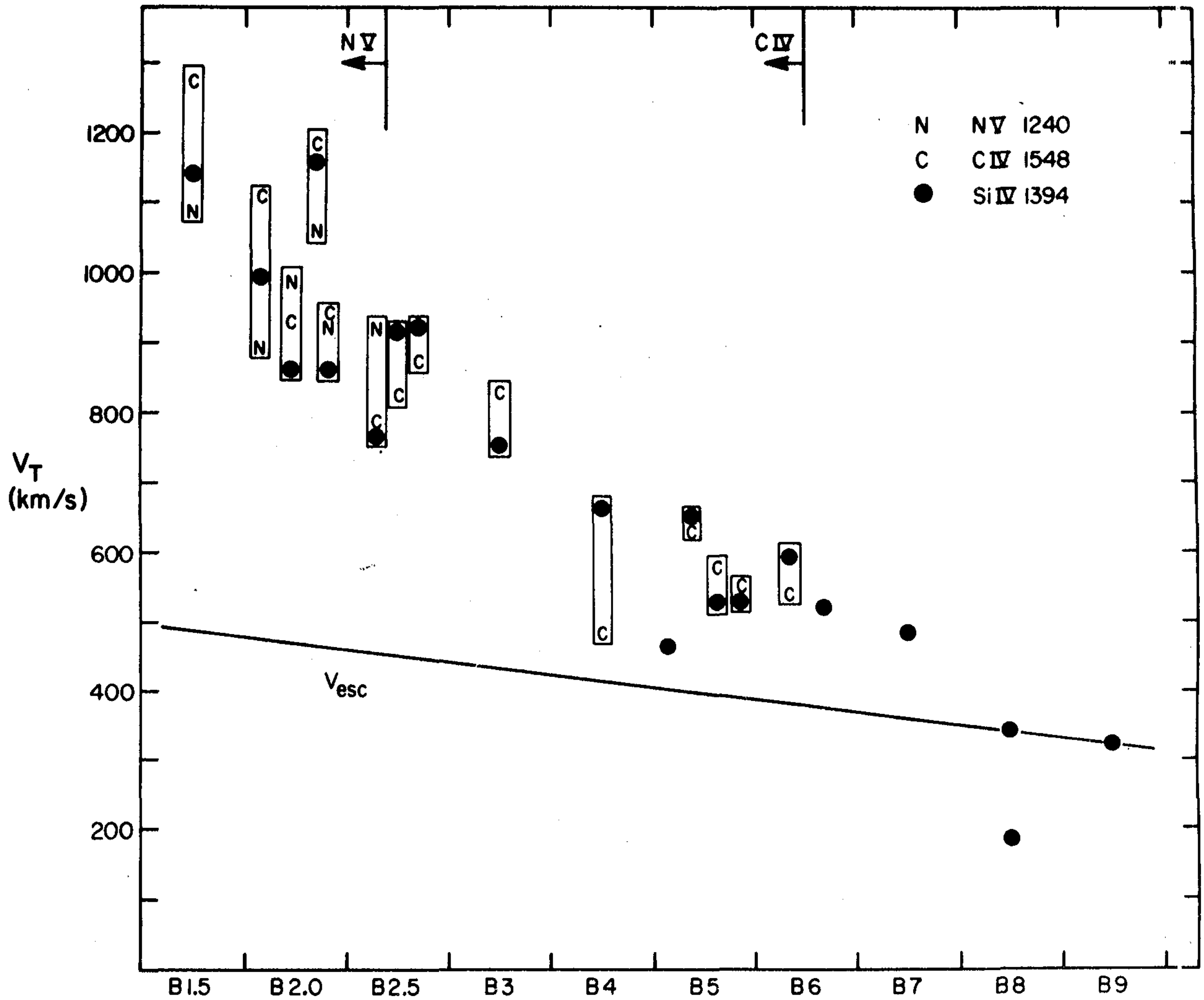

Fig. 4: Terminal velocities v_T derived from the resonance lines of N V, C IV and Si IV 1394. A box surrounds the measurements of one star in those cases in which more than one of the lines appears in the spectrum. Also shown in the run of escape speed for the supergiants of spectral type B1.5 to B9.