PART II.

General Summary of Results on « Astronomical Turbulence » in Stellar Atmospheres.

Summary-Introduction.

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1. – Introduction.

The term « astronomical turbulence » may be interpreted in a variety of ways. For the purposes of this paper, it is assumed that this expression is equivalent to the term « velocity fields ». Thus this paper will summarize our knowledge of (i) the magnitudes of the velocities occurring in the atmospheres of reasonably stable stars, (ii) the time-dependence, and (iii) the directional characteristics of the velocity fields that exist. Neither motions in the atmospheres of explosive variables, nor motions in the atmospheres of strictly periodic variables, nor solar phenomena will be discussed. This summary is restricted to spectrographic observations of stars that have not changed their character radically since they were first observed some fifty or sixty years ago. The stars which are studied can hardly all be classified as *stable* stars, for changes do occur in their light and spectrum, but in no case are the changes catastrophic.

The terminology used to describe the effects of motion in the stellar atmosphere on the stellar spectrum has grown up in a haphazard manner. This paper attempts to present a unified view of the relevant observations. On the whole, the unsatisfactory current terminology is used so that contact may be retained with the astrophysical literature from which the details are drawn. It is doubtful whether any of the velocity fields inferred here and called « turbulence » closely resemble the phenomenon known as turbulence in wind tunnels.

It has become customary to state that the observations give information about the *microscopic turbulence* and the *macroscopic turbulence* in stellar atmospheres. This division is essentially a result of the methods of analysis that are used.

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The *microscopic turbulent velocity* results from curve-of-growth analysis. It is mathematically similar to the most probable velocity of the atoms due to thermal motion. Thus the microscopic tubulent velocity field is assumed to obey a Gaussian distribution law. The exact meaning of the microscopic turbulent velocity is not clear, though it is a quantity that may be obtained by simple analytical methods. Often when stellar spectra are analysed, it turns out that the equivalent widths of the spectral lines obey a curve of growth corresponding to a greater « thermal » velocity than that appropriate to the temperature indicated by the degree of excitation to the various levels in the atom. The difference between the observed velocity and that corresponding to the excitation temperature is called microscopic turbulence.

The term *macroscopic turbulence* covers all irregular, non-periodic motions of the atoms in a stellar atmosphere which are detected by means other than the curve of growth. The macroscopic velocity field is detected from the shapes of the spectral lines, from occasional line doubling, and from the occasional displacement of spectral lines. The motions detected in these ways remain sensibly the same over regions in the stellar atmosphere which are large with respect to the distance in which an absorption line is effectively formed.

One of the greatest problems in the study of motions in stellar atmospheres is to find sensitive and significant means of observing these motions in adequate detail. In order to interpret the results, it is essential that one appreciate how the observations are made and what observations may be made.

In principle one may measure the following three quantities on any spectrogram: (i) the relative intensities of the absorption lines in the spectrum (ii) the shapes of the absorption and emission lines, and (iii) the displacements of the spectral lines. In practice meaningful information can be obtained only by strict attention to detail. All data reported in this paper have been obtained by photographic spectrophotometry.

1·1. *The relative intensity of absorption lines in a stellar spectrum.* – This type of data is fairly easy to obtain. The spectrographic observations must be made with sufficient spectral purity and resolution to isolate the lines being studied from the, often many, other lines in the spectrum, and reliable spectrophotometric techniques must be used. Experience has shown that a linear dispersion of at least 10 Å/mm is required; a dispersion of the order of 4 Å/mm is necessary for many purpose. All intensity measurements are relative to the apparent continuous spectrum in the neighbourhood of the line, the intensity of a line being expressed as an *equivalent width.* Definition of the apparent continuous spectrum is a subtle problem, for in most stellar spectra the absorption lines are very numerous and often overlap.

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When the spectral lines are broadened, for instance by motions of the stellar atmosphere, it becomes even more difficult to decide upon the level of the continuous spectrum. Very weak lines usually cannot be studied in detail.

1·2. *The shapes of the absorption and emission lines.* – It is only feasible to make measurements of the shapes of the spectral lines when the lines are somewhat broadened. Thus it turns out that line shapes are a source of useful information only for a few bright stars which have intrinsically wide lines of moderate depth. If the spectral lines are very wide and very shallow little useful information can be obtained because even in the best cases the photographic grain causes random fluctuations in the intensity profile of the order of three to five per cent of the continuous spectrum. Thus if the feature is only 10 to 15 per cent deep at most, the fractional uncertainty in the profile due to grain is large. In principle photoelectric spectral scanning would reduce the uncertainties due to photographic grain, but other practical difficulties may be encountered due to the faintness of the stars. At present, high-dispersion photoelectric scanning of stellar spectra is in its infancy.

1·3. *The displacements of the spectral lines.* – Measurement of the apparent wavelengths of the spectral lines determines a radial, or line-of-sight, velocity. If one knows something about the line-of-sight motion of the star, one can sometimes separate out motions occurring only in the atmosphere from the motion of the star as a whole. In order to investigate atmospheric motions one desires velocities with an uncertainty of 1 to 2 km/s at most. This means determining the positions of the spectral lines (blue-violet region) to about 0.02 Å. At a linear dispersion of 10 Å/mm it follows that the positions of the spectral lines must be determined to within about 0.002 mm on the plate. Such accuracy requires excellent techniques of measurement and well defined stellar features. At higher dispersion, it is easier to determine velocity changes of 1 or 2 km/s, for the linear scale on the spectrogram is larger.

In summary it may be said that information about motions in stellar atmospheres can be obtained from stellar spectra with a linear dispersion of 10 Å/mm or better, and that the spectral purity of the spectrograms must be good. Since only few observatories have spectrographic equipment of the necessary power, the observational data to be summarized have been obtained by only a few astronomers. It is unlikely that this body of data will be increased rapidly because each piece of information is the result of much painstaking labour and few astronomers are engaged in this type of work at present.

Before reviewing in detail the data that exist, let us consider the factors limiting further progress. On the theoretical side there are difficulties of inter-

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pretation. Since the stars are at great distances, we cannot observe their disks, and the light that reaches us is a weighted mean of the radiation emerging at all angles to the surface and from various depths in the atmosphere. Theories of the stellar spectrum attempt to tell how the observations should be inverted to yield information about the stellar atmosphere, but the theories are in many respects quite rudimentary. In a few special cases, the *ζ Aurigae* or *31 Cygni* stars, we can partially resolve the angular problem. In addition much purely physical knowledge about the interaction between radiation and atoms under stellar conditions is lacking. Our knowledge of f-values, and the shape of the line absorption coefficient under conditions of collisional and radiation broadening is not so complete as is necessary. This lack makes some interpretations uncertain and contradictory.

On the practical side, the faintness of the stars is a severe limitation. We have seen that good spectral purity and a linear dispersion of at least 10 Å/mm is required to obtain useful information about the motions in stellar atmospheres. This means that the stars must be observed with a large reflecting telescope and a powerful spectrograph. Except for the brightest stars the exposure time can quite easily amount to 6 or 8 h. Often a compromise is struck by opening the slit of the spectrograph fairly wide. This procedure, however, may throw away useful information. Furthermore a number of interesting bright stars are not accessible from the northern hemisphere where all active powerful spectrographs are located at present. Most stars have broad ill-defined spectral lines. Since it is only worthwhile to study stars with sharp lines at high dispersion, we are limited to a few objects, not always those that would appear to be most profitable for study.

Another limiting factor is the earth's atmosphere. This blanket permits observations only in certain wave-length regions and frequently only on isolated nights or parts of nights. The interstellar medium also can make the observation of distant objects difficult by dimming the blue-violet light and by impressing broad, ill-defined absorption lines over certain spectral regions that are of interest.

Investigations of the time-dependence of the velocity fields in stellar atmospheres are limited in two ways. 1) Phenomena that occur in periods of less than one or two hours cannot be investigated in detail at high dispersion because, unless the star is very bright, the exposure time to obtain a spectrogram will be longer than one hour. 2) Changes that occur in periods of 100 to 1 000 days cannot be investigated fully because frequently the necessary spectrograms were not obtained in the past. There is no way of turning back the clock to study phases that were missed, and there is equally no way of speeding up the clock to study the sequence of events at a rate faster than that at which they actually occur. Practically, the time-limitation is a powerful factor in determining what observations are made.

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2. – Microscopic turbulence.

STRUVE and ELVEY (1934) in an important paper showed that one could obtain an estimate of the motions in stellar atmospheres from an analysis of the equivalent widths (integrated absorption) of spectral lines. They showed that a velocity field in the stellar atmosphere would change the shape of the curve of growth, effectively prolonging the portion for which the equivalent width of the line varies directly as the abundance and lifting the so-called transition part of the curve of growth. The apparent result of increased, randomly directed velocities of the atoms on stellar spectra is to make the intrinsically strong lines more intense relative to the intrinsically weak lines. The results obtained by STRUVE and ELVEY are consistent with later work. Only the results concerning *17 Leporis* should be considered with reserve. STRUVE and ELVEY realized that *17 Leporis* is a shell star. Further observations have shown that the basic picture of a stellar atmosphere that underlies the method of curve-of-growth analysis does not describe the atmosphere of this star well.

Turbulent velocities have been derived by curve-of-growth methods for some 100 stars. A portion of this data has been summarized by WRIGHT (1955*a*). Further data may be found in the literature, particularly in papers concerned with abundances of the elements. The results to date are summarized in Table I.

TABLE I. – *Velocities from curve-of-growth analysis.*

No. of stars	Type of object		Microscopic turbulent velocity (km/s)
24	Population I:	luminosity classes IV and V	$1 \div 3$
43	»	luminosity classes II and III	$2 \div 6$
25	»	luminosity classes I*a* and I*b*	$2 \div 20$
4	Metallic line stars		4
2	Magnetic stars		$2 \div 5$
4	*T Tauri* stars		$3 \div 4$
2	Subdwarfs		1
5	Population II stars		4

At this point a few words should perhaps be interpolated to inform the non-astronomer on the terminology of Table I. Stars are classified according to the general appearance of their spectra (that is according to spectral type), and according to other properties such as their position in space and their space motion. Population I stars are the common stars which make up the

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spiral arms in the vicinity of the sun. Population II stars are stars having a radically different space motion. They are believed to compose the bulge of the galaxy and to be scattered thinly around the galaxy in a halo. Much evidence suggests that these stars are older than Population I stars. The metallic line stars are stars in which the absorption lines from the ionized and neutral metals are unusually strong in comparison to the hydrogen lines. Magnetic stars are stars which are known to possess strong magnetic fields. No test for magnetic field is known that can be used for all stars, thus there is no information about the presence or absence of a magnetic field for most stars. The *T Tauri* stars are comparatively cool, irregularily variable stars which have a spectrum containing emission lines like those of *T Tauri*. It is suspected that these stars are very young, and that they are still in the contracting stage. Subdwarfs are stars about one magnitude fainter than normal stars of the same spectral type.

A system of spectral classification (see, for instance, KEENAN and MORGAN, 1951) has been developed for the common, Population I stars. Each gross type is denoted by a letter. The gross types are subdivided into sometimes as many as ten subtypes which are indicated thus: B1, B2, B5. The spectral type classification is essentially a classification according to temperature, the spectral classes being arranged as in the following tabulation. The B1 stars are hotter than the B2 stars, the B2 stars hotter than the B5 stars, and so on. The average speed of a hydrogen atom at these various

Spectral type	Approximate temperature in the atmosphere (°K)	Average velocity of H atoms (km/s)
O	28 000 to 40 000	21.4 to 25.7
B	11 800 to 25 000	14.0 to 20.3
A	8 100 to 11 000	11.6 to 13.5
F	6 000 to 7 600	10.0 to 11.2
G	5 000 to 5 800	9.1 to 9.8
K	4 000 to 5 000	8.1 to 9.1
M	2 600 to 3 600	6.6 to 7.7

temperatures is listed as a convenient reference with which to compare the velocities of Table I. Stellar atmospheres are composed predominantly of hydrogen.

When a group of stars of a given spectral type is examined, it is found that the stars do not all have the same absolute brightness. Because such stars all have about the same surface temperature, this variation in intrinsic brightness (which may be anything from one magnitude to over ten magni-

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tudes) is essentially due to differing size. Hence the origin of the terms subdwarf, dwarf, giant, and supergiant star. This spread in size is reflected by a considerable range in pressure in the stellar atmospheres. In dwarf stars the pressure is about 10^4 dyn/cm^2, in giants it is about 10^2 dyn/cm^2, and in supergiants it may be about 10 dyn/cm^2. Stars may be separated according to their intrinsic luminosity (size) by carefully observing the relative intensity of certain spectral lines which are pressure sensitive. The Keenan-Morgan system makes use of « Luminosity Classes » to describe this differentiation. The supergiants fall in luminosity classes I*a* and I*b*, the giants in classes II and III, the dwarfs in classes IV and V. When stars are plotted on the spectral type-absolute luminosity plane, it is found that the points are not randomly distributed, but that they fall along certain well-defined sequences. Such a plot is called a Hertzsprung-Russel diagram (HR diagram) after the discoverers of this phenomenon. The HR diagram of Population I stars is different from that of Population II stars. One may infer that the differences are due to evolution changes (cf. Fig. 1 of DEUTSCH paper, part III-C for an HR diagram).

The significance of the numbers in Table I and specially the significance of the differences between the individual values included in these means are matters that require consideration. In the first place, any systematic errors in the equivalent widths will affect the estimate of the microscopic turbulent velocity directly, because this velocity is determined from the difference between the observed ordinate, log W/λ, and the theoretical ordinate, log $(W/\lambda)\cdot$ $\cdot(c/v)$. It is known that there are sometimes systematic differences between equivalent widths measured on different spectrograms. In part these are due to differences of interpretation of the stellar spectrum, in part they are due to insufficient resolving power of some of the spectrographs used, and in part they are due to faulty calibration of the photographic plates. It is sometimes a delicate task to maintain a calibrating device in proper order, and it often takes an experienced worker to realize that something is wrong. Unfortunately sufficient attention has not always been paid to the question of whether the calibration is good or not. Very few papers devote as much as a sentence or two to the question of whether the measured equivalent widths are what they are supposed to be. Photometric calibrations are rather like the little girl in the rhyme:

When they are good, they are very, very good,
But when they are bad, they are horrid.

Secondly, the shape of the theoretical curve of growth to which the observations are fitted is a function of the model used. Consequently, because there is a choice of models, there is a small intrinsic scatter in the value of the parameter v that may be derived from a given set of data.

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Thirdly, the observed points frequently do not define well a single curve of growth owing to uncertainties in the theoretical abscissa (log *gf* values), and to random errors in the measured equivalent widths. Usually the uncertainty in the derived value of $\log v$ is at least ± 0.1. The uncertainty of fit may be larger in cases such as the supergiants where it is quite doubtful whether any of the models underlying the method of analysis is applicable.

HUANG (1950, 1952) has considered some of these points from the theoretical point of view. He concludes that unless the real distribution function of the eddy velocities is known, the meaning of the turbulent velocity derived from the curve of growth is uncertain. Nevertheless, it seems probable that the parameter v does give an order of magnitude estimate of the most probable velocity differences between atoms in the line of sight.

The following generalizations appear to be secure.

1) Motions in stellar atmospheres increase as the luminosity of the stars increases. In the supergiants the microscopic turbulent velocity correlates with the excitation potential of the lower level from which the line arises. The correlation is in the direction that lines of low excitation potential reflect a larger range of velocity than do lines of high excitation. This correlation was first noticed by WRIGHT (1947). More recent data on supergiant spectra (see for instance ABT, 1958) confirm this trend. HUANG (1952) has shown that this behaviour is consistent with the assumption

$$v_{\text{turb}} = v_0 \exp\left[-\alpha\tau\right]$$

where τ is the optical depth in the continuous spectrum and v_0 and α are constants which vary from star to star. Since lines of high excitation are usually formed at deeper levels in the atmosphere than lines of low excitation, this relation suggests that turbulent velocities are less in deep layers.

2) The metallic line stars, peculiar A stars, and magnetic A stars appear to show a somewhat larger microscopic turbulence than do normal stars of similar luminosity. E. M. BURBIDGE and G. R. BURBIDGE (1955) have investigated how much of this increase might be due to magnetic effects. They conclude that the magnetic broadening would contribute about 1 km/s.

3) The *T Tauri* stars (BONSACK and GREENSTEIN, 1960) and the Population II stars (BURBIDGE and BURBIDGE, 1956) have rather greater microscopic turbulence than main sequence stars of roughly similar spectral types.

4) The subdwarfs show very little microscopic turbulence.

HUANG and STRUVE (1952, 1955) using the concept of large and small eddies, have introduced methods of analysing high dispersion spectra that attempt to take into account the fact that microscopic turbulence chiefly

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affects the equivalent width of a line while macroscopic turbulence affects chiefly the line shape. They note that if one plots the apparent half-width of the absorption-line profiles as $\log D_\lambda/\lambda$ (where D_λ is the half-width in wavelength units) against the equivalent width as $\log W/\lambda$, one obtains a curve of characteristic form. From the displacements necessary in both co-ordinates to fit the theoretical curve to the observed curve, one may estimate the most probable velocity of small eddies and the most probable velocity of large eddies. They also show that the slope near the origin of a plot of line depth against W/λ gives information on the contribution from large and small eddies.

These methods have been applied by HUANG and STRUVE (1952, 1953, 1955) to spectra of the supergiants *δ Canis Majoris* (F8I*a*), *α Cygni* (A2I*a*), and *ϱ Leonis* (B1I*b*); by WEHLAU (1956) to spectra of the double star *γ Leonis*, both components of which are giant stars; and by MICZAIKA and WADE (1958) to spectra of the metallic line star *8 Comae*. In each case it turns out that the most probable velocity of the small eddies is close to the value found from curve-of-growth studies, and that the most probable velocity of the large eddies is not much larger. In the case of *δ Canis Majoris* the relationship between excitation potential and microscopic turbulent velocity which is found by curve-of-growth analysis is reproduced by these methods.

The methods of line-width and line-depth correlation can only be used with spectrograms of the highest dispersion and resolution (about 3 Å/mm) and then only for stars with intrinsically wide lines.

3. – Macroscopic turbulence.

3·1. *Generalities.* – The concept of macroscopic turbulence has grown up in the last 15 years to explain detail observed on many high-dispersion spectrograms. However, since few observing programs have been directed towards investigating macroscopic turbulence in detail, the relevant material must be extracted from the results of other investigations. Because of the chance distribution of observations, one cannot investigate the time-dependence of macroscopic turbulence in as much detail as would seem desirable. In what follows, the term macroscopic turbulence is taken to mean all irregular, non-periodic motions in stellar atmospheres that occur in bodies of gas large with respect to the distance in which an absorption line is formed, that is, all motions which affect the line shape and position rather than the line strength and which change from time to time.

I must apologise to the non-astronomers present for speaking during the next few minutes in detail about a few selected stars. Only in this way can I put the data before you. Each star has a character of its own, and the available information about each illuminates some facet of the problem

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before us. I have selected stars for which considerable data (much of it yet unpublished) were available to me at the Dominion Astrophysical Observatory. Other persons would probably put other samples before you. However, I hope what I do present will give a fair sample of the fields of velocity which exist in some stellar atmospheres. Two things will become clear. (i) Large velocities can and do exist in the envelopes of low density gas around stars. (ii) These velocities change from time to time. The stars which are discussed have conspicuous envelopes and conspicuous macroturbulence. Little information can yet be deduced about cases where macroturbulence is not prominent.

How are the motions of atoms in different parts of a stellar atmosphere observed? In the first place only the line-of-sight or *radial* velocity component can be measured. This is found by the first order Doppler effect. The transverse Doppler effect gives displacements that are too small to be detected in stellar spectra. Since, with stars, one receives the light from all directions in one spectrogram, the possibility of separating out certain components of velocity depends upon the relative sizes of the *intrinsic* range of velocities which exists at the moment and the *effective* range introduced by limb-darkening and the projection factor. If there is a very skew distribution of velocity in the atmosphere, the spectral lines may become asymmetrical, shaded to the red or the violet depending upon the direction of the velocity field, or the lines may become double or even triple. Generally the velocity distribution is only sufficient to broaden the line in a symmetrical manner. Occasionally asymmetrical spectral lines are observed.

An estimate of the magnitude of the velocities occurring can be made by measuring the width and shape of the line profiles, and by measuring the displacement of the spectral lines. In order to conclude that a line is displaced, one must first know what the apparent wave-length should be when the line is not displaced. Since all stars are moving in space, and since one does not usually know the stellar velocity *a priori*, it is not always clear what the apparent wave-length of the undisplaced line should be. When the star is a member of a binary system, one can compute the line-of-sight motion of the star once the orbit is known. Then one can compute the apparent wave-length of each spectral line at any phase. A similar case is when the star is known to belong to a moving cluster or stream. Then one can assume, with reasonable confidence, that the motion of the star is known. Any apparent departure from this value can be credited to atmospheric motions. A weaker condition yet, is to assume that the star has a constant velocity. Then any apparent fluctuation in this velocity may be attributed to atmospheric motions. It is difficult at times to decide between perturbations in the star's motion due to membership in a binary system and fluctuations in radial velocity due to atmospheric motions.

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Ordinary main-sequence stars do not have *observable* extended atmospheres. We shall be concerned chiefly with supergiant stars and early-type stars which are surrounded by extended atmospheres or shells. It is wise to recall that if we could only observe the integrated light from the sun, for example as it is reflected from the moon, we would know very little about motions in the outer atmosphere of the sun. There is not enough material in the chromosphere and the corona for these parts of the solar atmosphere to contribute much to the integrated spectrum. The same is true for most main-sequence stars. Our knowledge of motions in the atmospheres of stars is severely limited by the means of observation available to us.

In general information about motions in stellar atmospheres will be given by the intrinsically strong absorption or emission lines from abundant elements. Roughly speaking an absorption line is not visible unless there is sufficient material in the line of sight to produce an optical depth of the order of unity. Since optical depth is measured by the product of the number of atoms in the line of sight capable of absorbing the line and the atomic absorption coefficient, it is clear that fewer atoms will form an observable feature when the line is intrinsically strong than when the line is weak. In order to investigate fully the velocity fields in stellar atmospheres we should like to be able to observe relatively small volumes of gas. This can only be done by means of very strong spectral lines.

It is certain that conditions of strict local thermodynamic equilibrium do not exist in all parts of the extended atmospheres where macroscopic turbulence occurs. However, not enough is known about the interactions between radiation and atoms that occur to make it worth-while to apply any detailed theory of line formation at present. Rather it is simply assumed that the line profile mimics the shape of the absorption coefficient and that line displacements relate directly to velocities. When the theory of line formation (absorption and emission) is sufficiently well understood, it may be worth-while to go over the observations and sharpen the interpretation.

Suitable spectral lines for revealing macroscopic turbulence in stellar atmospheres are the following:

in absorption:

— late-type stars: resonance lines, particularly of Ca II and Ca I, strong lines from levels of low excitation in the spectra of Fe I, Mn I, Cr I and Ti II chiefly;

— early-type stars: Balmer lines of hydrogen, and lines arising from metastable levels. These include certain He I lines and many lines of Fe II, Cr II, etc.;

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in emission:

— late-type stars: resonance lines of Ca II, selectively excited lines of low excitation, Balmer lines of hydrogen;

— early-type stars: Balmer lines of hydrogen, particularly H_α, selectively excited lines such as C III λ 5696, N III λ 4640, and He II λ 4686.

3·2. *Evidence for macroscopic turbulence in stellar atmospheres.*

3·2.1. Supergiants. – Supergiants of all spectral types are readily recognizable by the broad, steep-sided absorption lines in their spectra. The supergiant absorption lines are typically $\exp[-x^2]$ in shape with a flat bottom (peak). Realization that relatively large motions may occur in the atmospheres of supergiants stems from the observation by STRUVE (1946) that the strong lines in the spectrum of δ *Canis Majoris* are wider than the weak lines, and that the velocity spread corresponding to the profiles of the strong lines is significantly greater than that corresponding to the curve of growth. The theoretical implications of these details were discussed by UNSÖLD and STRUVE (1949). Many more observations are now available about the motions of gas in the atmospheres of supergiants and other stars. Some of these data will be presented.

All supergiants that have been observed photometrically over any considerable period are found to vary slightly and irregularly in light. Also, the radial velocity of most, it not all, supergiants varies irregularly by a small amount. Changes in line shape have been recorded for a few supergiants. More changes in line shape might be discovered if the supergiants were observed regularly at very high dispersion (2 to 3 Å/mm). Unfortunately such an observing program is rather impracticable.

Nearly everyone (see for instance HUANG (1953), SLETTEBAK (1956), and ABT (1958)) who has attempted to interpret the line profiles of the supergiants has noted that from the shape of the profiles alone one cannot differentiate between broadening due to rotation with an equatorial velocity of some 25 to 50 km/s and macroturbulence with a most probable velocity of the order of two-thirds the necessary rotation. Further information is required to resolve this difficulty.

The available information about velocities in the atmospheres of supergiants is summarized in Table II. The entries in this Table are explained in the following paragraphs. Unless credit is otherwise given, the material that is presented has been obtained by me from spectrograms taken at the Dominion Astrophysical Observatory by my colleagues and by myself. I am grateful for permission to use the extensive body of material which has been assembled at the Dominion Astrophysical Observatory over the years. What is presented here is a mere skimming of the field.

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TABLE II. – *Velocities occurring in the atmospheres of supergiants.*

Type of star	Radial velocity range (km/s)	Shapes of absorption lines (km/s)	Curve of growth (km/s)	H_α emission profile (km/s)	Moving shell and or clouds (km/s)	Chief objects studied
B I*a*	30	$20 \div 40$	$15 \div 30$?	~ 200	~ 200	χ^2 *Ori, 55 Cyg*
B I*b*	30	$20 \div 60$	15			*67 Oph, ϱ Leo*
A I*a*	$4 \div 20$	$12 \div 15$	13	(~ 200)	(~ 100)	α *Cyg*
A I*b*		$10 \div 20$	$5 \div 7$			H.R. 8345, H.R. 2874
F I*a*	$4 \div 20$	$15 \div 30$	$2 \div 26$			δ *CMa, ε Aur, 89 Her*
F I*b*		$6 \div 20$	6			α *Per*
K I*b*	$7 \div 10$	$10 \div 20$	$4 \div 13$		$\leqslant 100$	*31 Cyg*
M I*a*	$10 \div 20$				$10 \div 50$	α *Ori, VV Cep*

a) B-type supergiants. The stars χ^2 *Orionis* (B2I*a*), *55 Cygni* (B3I*a*), *67 Ophiuchi* (B5I*b*), and ϱ *Leonis* (B1I*b*), are representative of the early-type supergiants. All of the Victoria spectrograms of χ^2 *Orionis*, *55 Cygni* and *67 Ophiuchi* that have been obtained with resolving power better than one-prism were measured for radial velocity. The results are summarized in Table III.

TABLE III. – *Summary of radial velocity results for 5 B-type supergiants.*

Star	No. of spectrograms	First observation	Last observation	Range in radial velocity (km/s)	Remarks
χ^2 *Ori*	13	1938 Dec. 19	1959 Nov. 16	15	(1)
χ^2 *Ori*	74	1921 Feb. 20	1941 Jan. 18	30	(2)
55 Cyg	52	1959 Aug. 27	1959 Aug. 6	30	(3)
67 Oph	26	1943 July 2	1959 Aug. 6	30	(4)
H.D. 14134	18	1924 Sept. 12	1952 Nov. 23	29	(5)
H.D. 14143	16	1924 Sept. 12	1952 Nov. 23	33	(5)

(1) Fluctuations random and large.
(2) Mount Wilson observations; large fluctuations.
(3) Possible drift to more positive velocities; large fluctuations.
(4) Possible velocity peak in 1949.
(5) One-prism spectrograms measured by R. M. Petrie; large fluctuations.

The results of a long series of observations of χ^2 *Orionis* by R. E. WILSON at the Mount Wilson Observatory confirm and expand the Victoria results. WILSON published his material only in summary form (WILSON, 1953), but the manuscript results were most kindly forwarded to me from the Mount Wilson observatory. No attempt has been made to confirm whether or not

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WILSON used the same wave-lengths as those adopted here. For the present purpose the exact wave-lengths used are immaterial — all that is required is that the *same* wave-lengths be used for all spectrograms of a series. Also some observations due to R. M. PETRIE of two of the B-type supergiants in *h* and χ *Persei* are included.

The radial velocity of each of these stars fluctuates in an irregular manner, the range being greater than can readily be accounted for by the uncertainties of measurement. The observations are too scattered to rule out a regular, small-amplitude variation with a period of 10 to 20 days, but such a periodic variation does not seem probable. A survey of all available data for ϱ *Leonis* would likely give similar results. These radial-velocity fluctuations are most probably due to atmospheric motions.

Conspicuous changes of line shape have not been observed in the blue-violet part of the spectrum of any of these B-type supergiants. However,

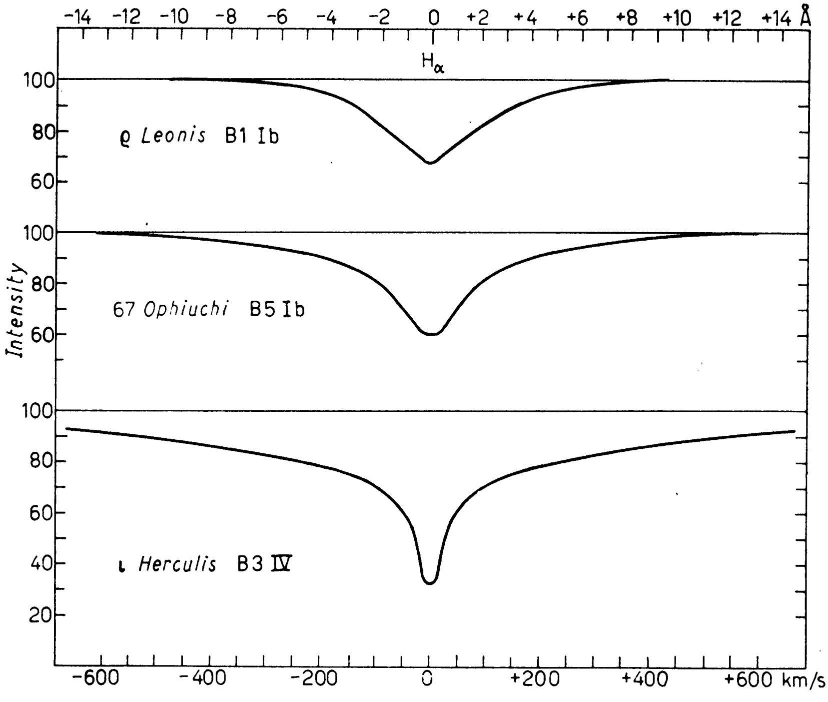

Fig. 1. – Profiles of H_α in the spectra of the B-type supergiants ϱ *Leonis* and *67 Ophiuchi*, and in the spectrum of the B-type main-sequence star *L Herculis*.

the profile of H_α changes from time to time in the case of the I*a* supergiants χ^2 *Orionis* and *55 Cygni*. The changes are shown in Figs. 1, 2, and 3, which contain all the data available at the Dominion Astrophysical Obser-

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vatory. These line profiles have been smoothed, and although the spectral purity (indicated by the length of the projected slit image) is not so great as might be desired, the profiles do give an impression of the changes that

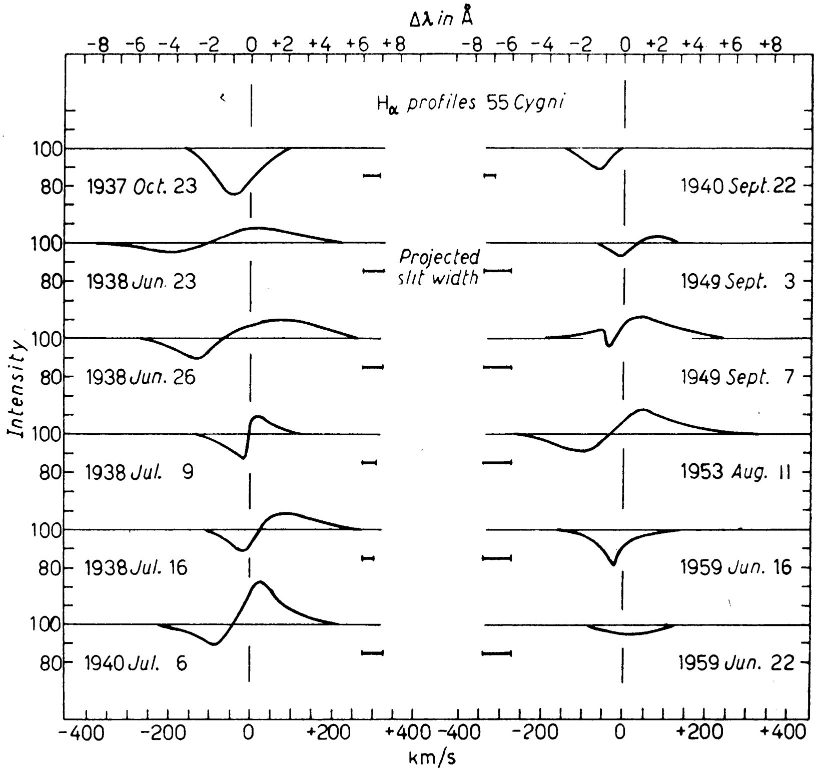

Fig. 2. – Profiles of H_α in the spectrum of the supergiant *55 Cygni* at various dates. It is clear that the emission intensity varies.

occur at H_α. Detail which is only as wide as the slit image, is by no means certain. The ups and downs have been traced as it seemed to me they appeared on the spectrograms; but the photographic grain is bad. The position of the undisplaced wave-length of H_α was determined by measuring the appropriate distance on the tracings from the positions of the C II lines λ 6578 and λ 6582 which are fairly well defined.

Fig. 1 displays the purely absorption profile of H_α in *67 Ophiuchi* (B5I*b*) and in *ϱ Leonis* (B1I*b*). These line profiles are what one would expect a normal stellar reversing layer to produce when the density is low, as in a supergiant. For comparison, the profile of H_α in *ι Herculis*, a B3 main-sequence star, is also shown. Here the effect of Stark broadening is evident. These line profiles have not changed by a detectable amount during the

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period of observation, and the position of the centre of the absorption dip agrees closely with the position projected from the position of the neighbouring C II lines.

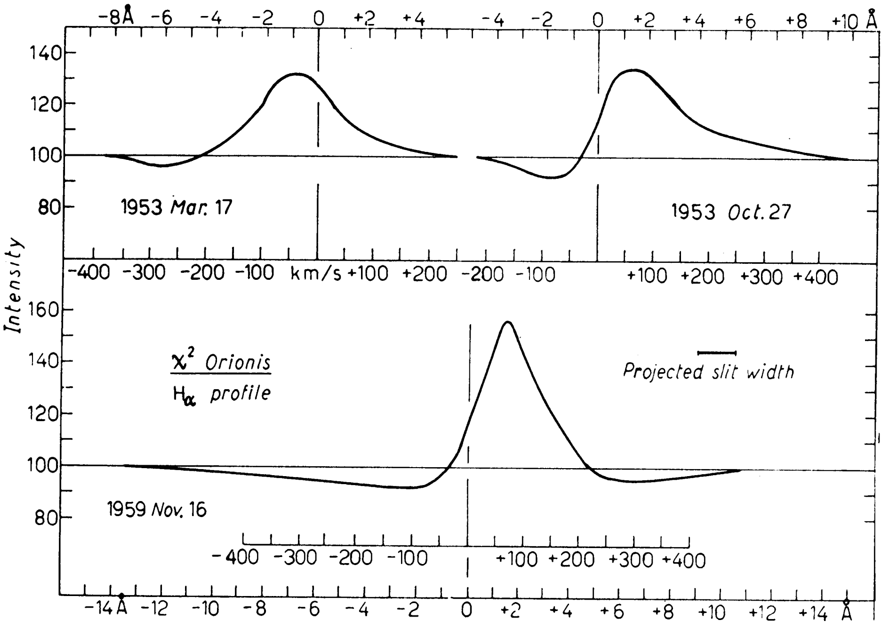

Fig. 3. – Profiles of H_α in the spectrum of the supergiant χ^2 *Orionis*. The shape and the intensity of this line varies from time to time. The projected slit width is 1.5 Å in each case.

Fig. 2 displays the profile of H_α in *55 Cygni* at various dates. At times only a weak absorption feature is visible; at times there is emission accompanied by violet-displaced absorption, the emission varying in strength and shape; at times there is no distinct feature either in emission or in absorption. The emission wings may extend 200 km/s from the centre of the line.

Fig. 3 shows the profile of H_α in χ^2 *Orionis* upon three occasions. The emission is stronger than in *55 Cygni*, and the emission wings extend to at least 200 km/s from the centre of the line. The shape and strength of the emission is variable. It is quite noticeable that the position of the most intense part of the emission feature shifts.

These data are barely reliable enough to do more than indicate the large changes that occur in the velocity of the gas and in the quantity of gas in the envelopes around these stars. There is no doubt that the H_α emission is more than 200 km/s wide at times in *55 Cygni* and in χ^2 *Orionis*. At other times it has nearly vanished. These changes in the shape and strength of

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the H_α line in the very luminous stars are almost certainly due to changes in the velocity and density of the gas around these stars. They are not due to Stark effect. It is quite possible that corresponding changes might be detected in the strong absorption lines of the blue-violet spectral region were spectrograms of sufficiently high resolution and spectral purity obtained. It is a significant point that the H_α line appears to be a normal absorption line constant in shape in the I*b* supergiants *67 Ophiuchi* and *ϱ Leonis*. An obvious inference is that the extremely luminous supergiants are surrounded by larger envelopes of moving gas than are the less luminous supergiants. Since the absorption component which accompanies the emission feature in the I*a* stars is displaced to the violet, it would seem that on the average the gas is moving away from the stellar surface. The emitting volume must be quite large, for the emission fills in almost completely the underlying absorption H_α profile which would be expected to originate in the stellar reversing layer proper. A hint of this underlying line is seen on the spectrogram of χ^2 *Orionis* obtained November 16, 1959.

VOIGT (1952) and ALLER (1956) have attempted to analyse the spectrum of *55 Cygni* by curve-of-growth and line-profile methods. ALLER concludes that the curve of growth is inconclusive on turbulent velocity, and that perhaps a macroscopic turbulence of 18 km/s would represent the line profiles better than the value of 36 km/s suggested by VOIGT. All attempts that have been made to interpret the line profiles in the blue-violet part of the spectrum of B-type stars of luminosity classes II, I*b*, and I*a* have indicated that velocities of the order of 20 to 30 km/s at least occur in the atmospheres of these stars. The H_α profiles in the spectra of the I*a* stars make visible much larger velocities. GOLDBERG (1939) has made curve-of-growth studies of a number of B stars.

b) A-type supergiants. The star α *Cygni* (A2I*a*) is the A-type supergiant which has been studied most, for it is apparently bright. The radial velocity of this star varies. PADDOCK (1935) at the Lick Observatory obtained many spectrograms in the years 1928-31, and he has published the results in detail. The note in the *Lick Radial Velocity Catalogue* (MOORE, 1932) summarizes the situation succinctly: «The velocities vary from $+6$ km/s to -9 km/s in the interval, but the character of the variation is such that it would be misleading to attempt to assign an adopted value for the velocity of this star». This would be a suitable description of the radial velocity results reported above for five B-type supergiants. The maximum range of the velocity variation of α *Cygni* is about 15 km/s. In addition α *Cygni* is known to be a light variable of small range (for references, see ABT, 1957). STRUVE and HUANG (1955) have studied line shapes in the spectrum of α *Cygni* from one spectrogram, and they estimate that the most probable velocity

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of the small eddies is about 15 km/s, whereas that of the large eddies is greater than or equal to 12 km/s. Curve-of-growth studies (BUSCOMBE, 1951) give v equal to 13 km/s.

The most extensive investigation of A-type supergiants is that by ABT (1957, 1958). In 1956 ABT took spectrograms of 6 I*a* supergiants every night for one month. He found that each varied in velocity, the range lying between 4 and 20 km/s. ABT inclined to the view that the variations were periodic, the characteristic period being about 7 to 9 days. It is doubtful whether extended observations over several years would confirm this periodicity. It is more probable that the radial velocity of each supergiant would continue to vary irregularly with a range somewhat as found by ABT. These variations are probably due to atmospheric motions, for ABT finds differences in the velocity derived from lines of different ionic spectra and from hydrogen. The ranges exhibited by the A-type supergiants are slightly smaller than those found for the B-type supergiants. ABT (1958) gives information about line shapes in the spectra of some AI*b* and FI*b* supergiants.

BEALS (1951) has noted that emission appears at H_α in the spectrum of α *Cygni* accompanied by a violet-displaced absorption feature. The emission feature seems to be variable in intensity, but no quantitative data exist at present. An inspection of the Victoria spectrograms gives the impression that the emission feature is quite wide, the emission perhaps extending 100 km/s from the undisplaced centre of the line.

c) F and G-type supergiants. The supergiant δ *Canis Majoris* (F8I*a*) is the first star for which the effects of macroscopic turbulence were recognized. STRUVE (1946) noted that the profiles of the strongest lines had shapes suggesting a most probable velocity near 30 km/s, while the curve of growth is consistent only with a velocity of the order of 5 km/s. The radial velocity observations of this star (CAMPBELL and MOORE, 1928) indicate a probable slow variation with a range of about 6 km/s. ABT (1957) found no significant variation during the short period of his observations. ABT observed 3 other F-type supergiants for radial-velocity and he finds that radial-velocity fluctuations occur in a matter of days, the range being about 4 km/s.

Much attention has been directed to the F0I*a* supergiant ε *Aurigae*. This star is the brighter component of an eclipsing system which has a period of some 27 years. Near conjunction, when the fainter star is moving in front of the F-type supergiant, extra, relatively sharp F-type lines are observed in the spectrum. These components occasionally are double or triple. Although there is no unanimous interpretation of the ε *Aurigae* system, quite plausible arguments may be advanced that the companion is a Be star. However, we do not wish to digress upon the fascinating peculiarities of ε *Aurigae*. The detailed work on this supergiant has shown the following facts

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relevant to the present discussion:

1) Irregular fluctuations, which are probably due to atmospheric motions, occur in the radial velocity of this star. The range is some 10 to 15 km/s and there are indications that lines from different ions give different velocities, that is, that there is a velocity gradient through the atmosphere.

2) The light of *ε Aurigae* varies irregularly by about 0.2 mag, quite apart from the light changes due to the eclipse.

3) The line profiles of the F-type supergiant change in shape from time to time. This behaviour was first noticed by WRIGHT (1955*b*) and it is very apparent on Wright's most recent series of high dispersion spectrograms. The most probable cause of these changes is change in the velocity field of the atmosphere.

In order to obtain a quantitative measure of the changes in line shape that occur, and thus to estimate the changes in the velocity field, I measured the profile of Mg II $\lambda4481$ on a series of intensity tracings of spectrograms obtained by WRIGHT between November 16, 1956 and May 15, 1957. During this period, the star was coming out of eclipse, and extra components were visible at some lines. However, an extra component does not appear for Mg II $\lambda4481$ because the lower level of this line is not metastable. Therefore, the shape of $\lambda4481$ reflects the distribution of velocities in the stellar atmosphere and not atmospheric effects associated with the eclipse. The shape of the profile was determined by fitting it to a Voigt profile (VAN DE HULST and REESINCK, 1947). It turns out that the parameter β_1 which represents the dispersion part of the profile is small and of little importance. Effectively, the line is fitted to a curve of the form $\exp[-(\Delta\lambda/\beta_2)^2]$. The resulting values of β_2 are shown in Fig. 4, plotted against time. The parameter β_2 is expressed in km/s. It is obvious that β_2 varies from over 100 km/s to somewhat less than 70 km/s in a few days. This means that the apparent halfwidth of the profile changes by some 30 km/s in a quite irregular manner. The line at no times has extensive wings. (The Mg II $\lambda4481$ line is a natural doublet of 0.2 Å separation and it is not quite resolved on the present spectrograms. The turbulent broadening to which the observations refer is superposed on the natural doubling).

Somewhat similar changes of line shape have been observed for *89 Herculis*, an F2I*a* supergiant (BÖHM-VITENSE, 1956). The light (WORLEY, 1956) and radial velocity of this star vary, the range of the radial velocity being 20 km/s.

Another very luminous star, *ϱ Cassiopeiae*, shows related spectral changes (BIDELMAN and MCKELLAR, 1957). The light of this star has recently changed by two magnitudes, and the spectral type has changed from F8I*a* to some-

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thing like G8I*a*. At present many of the lines of this star are double, the extra component being displaced some 35 km/s to the violet of the component due to the normal reversing layer. Presumably this star is ejecting material,

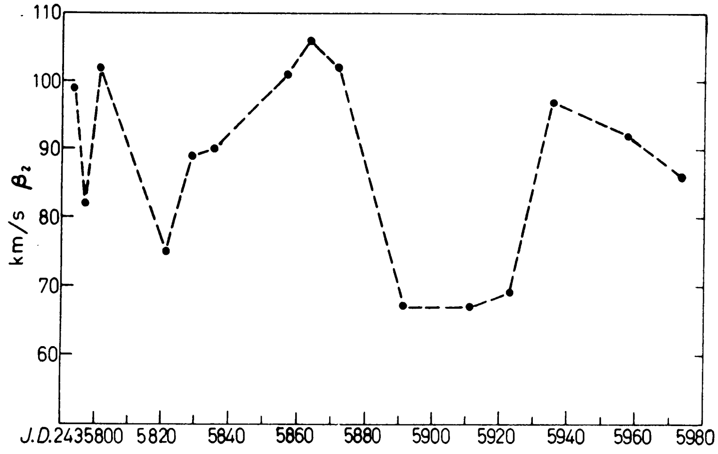

Fig. 4. – The variation of line width in the spectrum of *ε Aurigae*. The parameter β_2 measures the apparent width of the unresolved doublet Mg II λ 4481.

for considerable evidence pointing to an extensive shell exists. At all times the spectral lines of *ϱ Cassiopeiae* have the appearence considered to be characteristic of large « macroturbulence ».

d) K-type supergiants. The K-type supergiant for which we have the most detailed knowledge of atmospheric phenomena is 31 *Cygni*, K3I*b*. This star is the primary component of an eclipsing system, the secondary of which is a B3V star. This system is particularly valuable because, as the B star passes behind the K star, the light from the B star probes the extensive supergiant atmosphere. A sketch of the system is shown in Fig. 5.

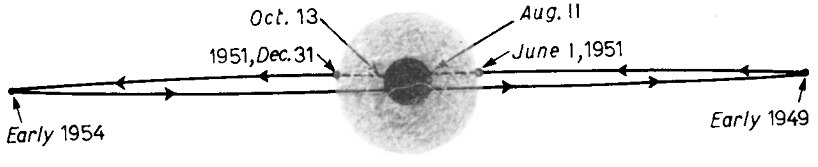

Fig. 5. – The eclipsing system *31 Cygni*. The extended atmosphere of the K-type supergiant is shown as a shaded area. The disk of the K star is drawn as a black circle. The B-type star is shown by a small dot. Chromospheric absorption lines are observed as the B star moves behind the atmosphere of the K star.

Extra absorption lines appear in the composite spectrum as totality approaches, the strengths and shapes of which reflect the properties of that part of the

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K-type atmosphere which is projected on the disk of the B star. Analysis of the displacements, shapes, and intensities of these so-called chromospheric lines gives some indication of the physical properties of the K-type atmosphere, particularly of the variation of the density and velocity fields with height above the limb of the K star. The complete atmospheric eclipse takes some 80 days, the daily motion of the B star being $3.87 \cdot 10^6$ km. Thus *31 Cygni* is one case where a fairly reliable *linear* scale may be inferred for a supergiant atmosphere. Extensive observations have been made at the Dominion Astrophysical Observatory and elsewhere; detailed accounts of the system are given by McKellar and Petrie (1959), McKellar, Aller, Odgers, and Richardson (1959), Wright and Lee (1959), and Wright (1959).

When the B star begins to go behind the atmosphere of the K star, the intrinsically strong *H* and *K* lines of Ca II form the first chromospheric components to appear. These absorption lines strengthen as the projected position of the B star gets closer ot the limb of the K star. At times several absorption components due to Ca II *H* and *K* are seen. These absorption lines provide unmistakable evidence that bodies of gas moving with discrete velocities exist in supergiant atmospheres. These « clouds » are observed to have relative velocities in the line of sight of up to 100 km/s, and the dimensions of the clouds are about 10^7 km. Near the limb of the K star, at about 3 days or $12 \cdot 10^6$ km out, the density of the K-type atmosphere suddenly increases and many lines of Fe I, Ti II, etc. appear as chromospheric components.

The apparent wave-lengths of the Ca II chromospheric lines indicate erratic departures from the orbital radial velocity. These departures are probably due to atmospheric motions. The range is 7 km/s.

The shapes of the line profiles of the chromospheric components may be fitted best by a most probable turbulent velocity of 20 km/s in the inner chromosphere, and by a most probable turbulent velocity of 10 km/s in the outer chromosphere.

Wright (1959) has made curve-of-growth analyses of the chromospheric spectrum. He derives microscopic turbulent velocities of 4 to 13 km/s from lines of Ca I, Sc II, Ti I, Ti II, Fe I, Co I, and Ni I. The results are effectively the same for neutral and ionized atoms. The results are most comprehensive for Fe I where the curve of growth indicates that the microscopic turbulent velocity is about 7 to 8 km/s in the inner chromosphere (within 3 days of totality), but beyond 5 days the value increases to 12 km/s. This analysis gives an « excitation temperature » increasing outwards from 2 750° at the limb to 5 500° at 18.7 days out ($69 \cdot 10^6$ km).

Faint emission lines due to Ca II *H* and *K* appear in the bottoms of the strong stellar Ca II *H* and *K* absorption lines in the spectra of most, if not all, G and K-type stars. O. C. Wilson and Vainu Bappu (1956) made the

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first systematic observations of these features. They noted that the apparent width of the emission lines correlates directly with luminosity. The emission features are widest in the most luminous stars. Presumably this correlation, which affords a convenient, empirical means of estimating the luminosity of G- and K-type stars, is a manifestation of the velocity fields present in G- and K-type atmospheres.

e) M-type supergiants. Supergiant M-type stars have extremely extended atmospheres. It is not unusual for the diameter of an M-type supergiant to be one thousand times that of the sun. Consequently, the gravitational control of the gas in these atmospheres is small, and large scale, irregular motions can develop. The radial velocities of a few M-type supergiants have been observed in detail, and in each case large random irregularities occur, the range being about 10 to 20 km/s. The line profiles are broad and steep-sided. On spectrograms of the highest dispersion many spectral lines appear double. Part of the doubling is due to the occurrence of emission components in the centres of strong lines, but part seems to be due to atmospheric motions. In addition, certain sharp, displaced absorption lines appear. These lines may be attributed to absorption in a very low density shell of gas surrounding the whole system and expanding from the star.

High-dispersion spectrograms of the eclipsing system *VV Cephei*, which consists of an M2 supergiant and Be star, and which forms a system geometrically similar to the *31 Cygni* system, reveal detail generally similar to that observed for *31 Cygni*. Thus, extra chromospheric lines are observed as the Be star begins to go behind the vast M-type atmosphere. These chromospheric lines indicate that discrete clouds probably occur in the M-type atmosphere and that these clouds may have relative velocities as high as 50 km/s. Also a circum-system envelope expanding at a rate of about 20 km/s is observed. The period of the *VV Cephei* system is 20.3 years and totality lasts some 450 days. Spectroscopic effects as the Be star passes behind the M-type atmosphere are visible at least a year before and a year after totality. The total phases of the latest eclipse commenced about July 28, 1956 and the stars are now separating. Brief descriptions of the spectroscopic peculiarities that occur are given by WRIGHT and MCKELLAR (1956) and by MCKELLAR, WRIGHT, and FRANCIS (1957). These authors also list references to earlier work from low dispersion spectrograms. There seems little doubt that velocities as high as 50 km/s occur in the atmosphere of the M-type supergiant.

3·2.2. Main-sequence stars. – Macroscopic turbulence is observed in the extensive envelopes or shells surrounding a few early-type main-sequence stars. Most ordinary, dwarf or main-sequence stars are not surrounded by

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observable shells, thus the data to be summarized now are characteristic only of a small fraction of the stellar population. Many main-sequence stars may have outer atmospheres similar to the solar chromosphere and corona, but at present there is no method of observing envelopes which contain little material.

The profile of H_α is one of the most sensitive indicators of the velocity fields in the envelopes around early-type stars, for H_α is an intrinsically strong spectral line from an abundant element. Even though the fraction of neutral hydrogen lies in the range 10^{-3} to 10^{-6} over much of a B-type shell, there are still enough atoms emitting and absorbing the Balmer lines to make the hydrogen lines sensitive probes of physical conditions in the shells.

When one is concerned with a low-density extensive atmosphere around a star, a spectral line will appear in emission if the shell is transparent to radiation from the neighbouring continuous spectrum, but opaque to line radiation, and if the shell is considerably bigger than the star. A few spectral lines are selectively excited in emission by special processes involving unobservable, strong emission lines in the extreme ultraviolet.

The available information about velocities in the extended atmospheres surrounding some main-sequence stars is summarized in Table IV. The various items are explained in the following paragraphs.

TABLE IV. – *Velocities occurring in the extended atmospheres around main-sequence stars.*

Type of star	Radial velocity range (km/s)	Shape of absorption lines (km/s)	Shape of emission lines (km/s)	Expanding shell (km/s)	Chief objects studied
Be			200 ÷ 400		*β CMi, η Tau, ϰ Dra*
B shell	10 to 80	50	600 ÷ 1000	?	*48 Lib, ζ Tau*
Of	30		100 ÷ 1500	?	*9 Sge*
WC	30		700 ÷ 1000	– 1200	H.D. 192103
WN	30		1000 ÷ 1500	– 1400	H.D. 192163

a) Be stars and B-type shell stars. When emission lines of hydrogen are observed superimposed on a B-type spectrum, the star is called a Be star. If in addition extra absorption lines (which usually mimic an A-type supergiant spectrum) are observed, the star is called a B-type shell star. A shell star appears to be similar to a Be star, the outer envelope, or shell, merely being larger and containing more material. These outer envelopes are frequently temporary features. Some stars have been observed to vary from B to Be, to shell star in less than 50 years. Many spectra have been taken of a few bright shell stars, and each series of observations usually

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gives ample evidence that the material in the shell is moving with velocities of ten to several hundred kilometers per second. The motion is largely directed outwards. Gradients of velocity sometimes exist in a shell. This is indicated by the observation that sometimes the absorption lines are asymmetrical, and by Merrill's discovery that in some stars the velocity shown by a high member of the Balmer series, say $H25$, is more negative than that shown by an early member of the series, say H_γ. Usually the « Balmer progression », as this phenomenon of changing velocity with series member is called, is such to indicate that the inner layers of the shell are moving outwards more rapidly than the outer layers. MERRILL has observed one or two reversed Balmer progressions, but in these cases the velocity spread is never so large as when the motion is predominantly outwards.

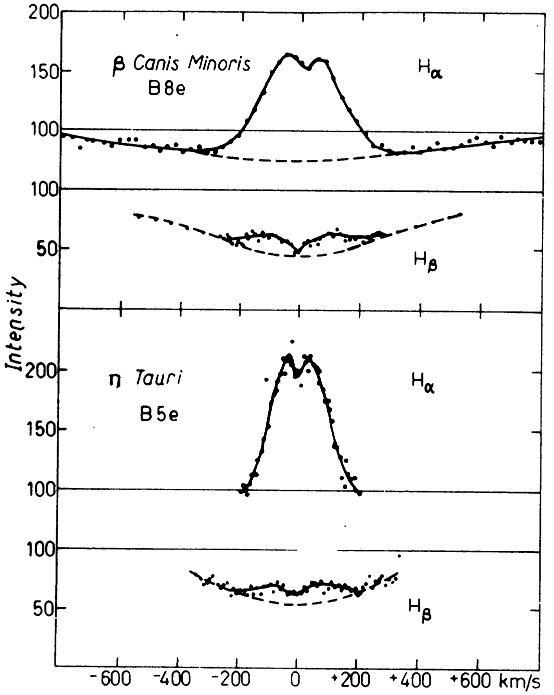

Fig. 6. – Profiles of H_α and H_β in the spectra of the Be stars *β Canis Minoris* and *η Tauri*. In these stars, the width of the H_α emission is about the same as that of the H_β emission on a velocity scale.

Profiles of H_α and H_β in the Be stars *β Canis Minoris*, *η Tauri* and *κ Draconis* are shown in Figs. 6 and 7. The width of the H_α emission profile is about the same as that of the H_β emission profile. A few atoms appear to have velocities up to 400 km/s though most of the emission occurs within 200 km/s of the line centre. Figs. 8 and 9 present line profiles of H_α and H_β in the spectra of the shell stars *48 Librae* and *ζ Tauri*. Two points are significant: (i) the emission is much wider and stronger in the shell stars than in the Be stars, and (ii) the extent of the wings in shell stars suggest velocities approaching 1 000 km/s. It is not certain whether the extent of the emission line profile in shell spectra is due solely to the velocity field, or whether it is partially due to abundance broadening (radiation broadening wings). It is quite unlikely that Stark broadening is significant at the estimated density of shells, 10^{11} particles/cm^3. Significant changes in the velocity fields in shells usually occur slowly. Very rapid changes, in periods of the

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order of a day, are not common. Some shells appear to be stationary, undergoing no change for years; others vary in a quasi-periodic manner. For a summary of further details of shell spectra, see UNDERHILL (1959*a*). The underlying B-type star is rotating rapidly in all cases which show strong shell spectra.

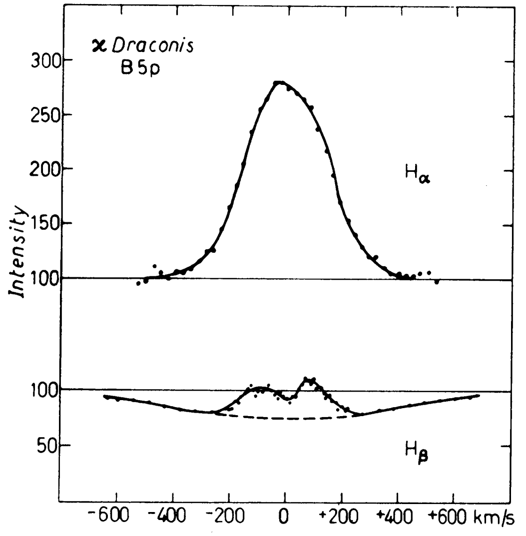

Fig. 7. – Profiles of H_α and H_β in the spectrum of the Be star *ϰ Draconis*. Here the H_α emission is more intense and it is wider than the H_β emission.

The radial velocity fluctuations of shell stars are usually in the range 10 to 20 km/s but outward directed velocities of 70 to 80 km/s are observed at times in the shell of 48 *Librae*, to give one example.

The shapes, strengths and displacements of the relatively sharp absorption shell lines reflect the changing density and velocity fields of that part of the shell which is projected against the disk of the star. However, since the emission lines arise from the whole of the optically thin atmosphere, the profiles of the emission lines reflect the overall velocity field of the shell. It is interesting that the few quantitative observations that are available indicate that the wings

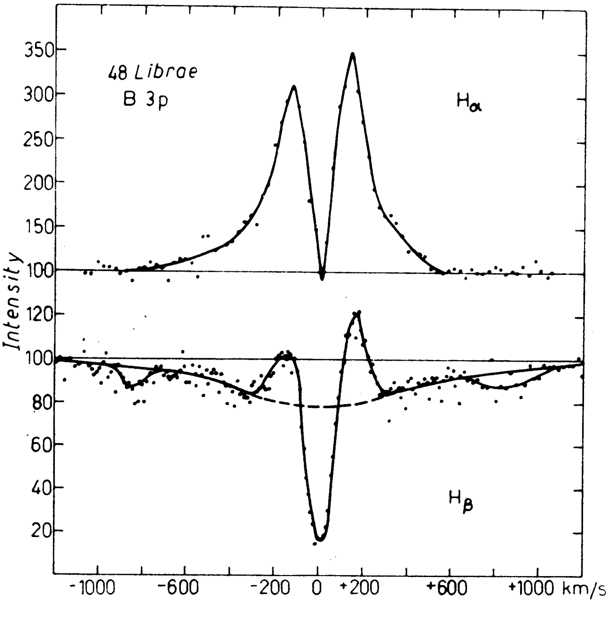

Fig. 8. – Profiles of H_α and H_β in the spectrum of the shell star *48 Librae*. Here the emission at H_α is much stronger and wider than at H_β, and there is a strong self-reversal in each line due to the relatively dense material lying in front of the stellar disk.

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of the emission H_α profile in *48 Librae* remain constant in shape, even though the local velocity fields revealed by the absorption components change by a large amount in a few years. An expanding, low density atmosphere with local velocity irregularities in the inner more dense sections would explain the observations qualitatively.

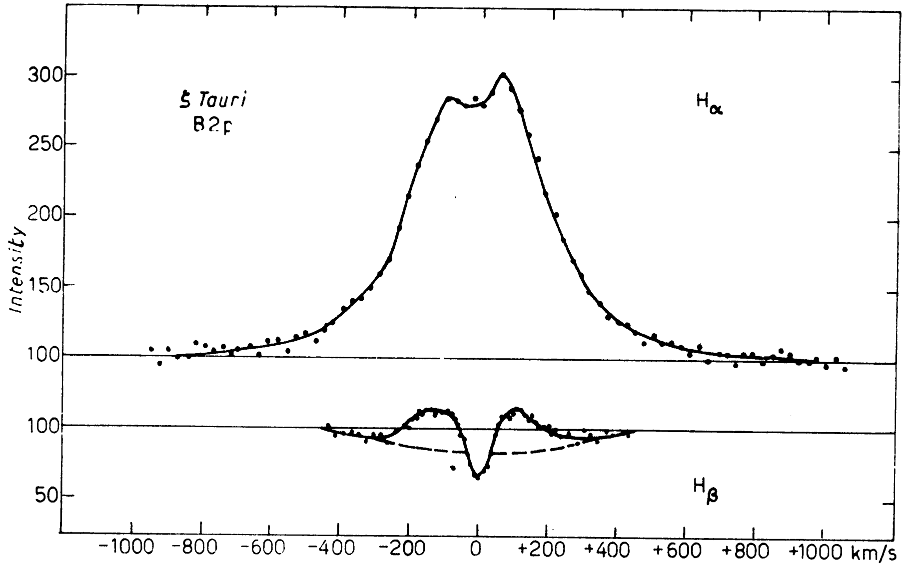

Fig. 9. – Profiles of H_α and H_β in the spectrum of the shell star *ζ Tauri*. Here the emission feature at H_α has very wide wings and the central reversals are not so strong as for *48 Librae*.

b) Of stars. The Of stars are stars of type O8 and earlier in which the lines He II λ4686, and N III λ4634-41 appear in emission. These lines may also appear in emission in the spectra of the O9 supergiants. (They probably are excited by selective processes in any low density gas around an object which has an effective temperature greater than about 30000°). Little quantitative work has been done on Of spectra, for there are few bright Of stars accessible from the northern hemisphere. It would appear that the Of stars are related to the Be and B-type shell stars. Each Of star probably consists of a main-sequence O-type star surrounded by a more or less extensive envelope or shell.

R. Wilson (1957) from detailed study of low dispersion spectra obtained at the Edinburgh Observatory made the significant discovery that the emission lines in Of stars have wide, low intensity wings extending some 1500 km/s or so from the line centre. Thus large motions occur in the envelopes around O-type stars. The more intense parts of the emission lines are relatively narrow, corresponding in the case of *9 Sagittae*, O7f, to a velocity spread of 100 to

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500 km/s (UNDERHILL, 1959*c*). The radial velocity of *9 Sagittae* varies irregularly with a range of 30 km/s (UNDERHILL, 1958).

c) Wolf-Rayet stars. The spectra of Wolf-Rayet stars are quite extraordinary in comparison to normal stellar spectra, for they consist of many wide, strong emission lines (frequently called bands though they have nothing to do with molecular band spectra), and a few comparatively sharp absorption components. The level of excitation is very high, the spectra consisting of lines of He I, He II, C III, C IV, N II to N V, O II to O VI, etc. A peculiar selectivity is apparent, in that when lines of C II, C III, and the spectra from the oxygen ions dominate, lines from the spectra of nitrogen ions are weak and *vice-versa*. The situation regarding interpretation is further confused by the fact that about half of the known Wolf-Rayet stars are binaries. One then obtains the spectra of both stars superposed. The companion is usually an absorption-line O or B-type star. Since the Wolf-Rayet stars accessible from the northern hemisphere are faint for observation at high dispersion, little work has been done with a spectral purity sufficient to resolve these complex spectra properly.

The following facts relevant to the present discussion were confirmed by a detailed study of the spectra of H.D. 192103, WC7 and of H.D. 192163, WN6, (UNDERHLIL, 1959*b*). These two stars appear to be single. The spectrum of the WN star contains lines of a higher level of excitation than does the spectrum of the WC star. It was early recognized, from comparison with nova spectra, that the shapes of the emission lines in Wolf-Rayet spectra were probably determined by the velocity fields in the atmospheres of these stars, but a consistent picture was not developed, partly because the interpretation of certain key observations was not clear when the first work was done. In the light of present knowledge about the production of stellar spectra the following statements probably correctly describe the main features of the velocity fields in the atmospheres of Wolf-Rayet stars.

1. The velocity fields in the inner, more dense parts of the atmosphere are randomly directed. In H.D. 192103 (a Wolf-Rayet star with a spectrum of comparatively low excitation), the total half-width of the He II emission lines from the 3-*n*, 4-*n* and 5-*n* series is 1300 km/s; in H.D. 192163 (a Wolf-Rayet star with a spectrum of relatively high excitation), the total half-width is 2000 km/s. There is some evidence that self-absorption occurs for the strongest He II lines. Relatively sharp, displaced absorption components are not observed for the He II lines, thus the simple picture of emission and absorption in an expanding shell of moderate dimensions is not adequate to describe the situation. A similar conclusion may be drawn from the detailed study of the spectrum of *V444 Cygni*, an eclipsing binary, one component of which is a Wolf-Rayet star.

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2. An expanding shell of low density gas does exist around Wolf-Rayet stars. This shell is at some distance from the stellar surface, for it is observable only in spectral lines which are enhanced in a low density gas which is irradiated by a high-temperature, dilute radiation field. Such lines are the He I lines arising from the $2\,^3S$ metastable level and from the $2\,^3P$ level, and equivalent lines in the spectra of C III and N IV which have electronic structures outside the closed $1s^2$ shell similar to that of He I. These lines appear in absorption, and they are the only obvious absorption lines appearing in the spectra of H.D. 192163 and H.D. 192103. The *outflow* motions made visible in this way are −1200 km/s for H.D. 192103 and −1400 km/s for H.D. 192163. In the cooler star, H.D. 192103, the C III line λ5696 appears in emission. The profile of this line is wider and more flat-topped than the profiles of the He II lines. The C III λ5696 line may be selectively excited in a low density gas which contains C^+ ions and through which a flux of He II λ303 is flowing (UNDERHILL, 1957). The total half-width of λ5696 in H.D. 192103 is 1860 km/s. Thus it seems reasonable to conclude that the profile of λ5696 confirms the existence of the low density, expanding shell observed by means of the absorption lines. This expanding envelope is in addition to the denser atmosphere in which most of the spectral features are formed.

So little is understood about the excitation and production of Wolf-Rayet spectra at the present time that no secure guess may be made about the temperatures of these objects. It would appear that the radiation field corresponds to temperature in the range 40 000° to 100 000°. Qualitatively there is a considerable resemblence between the atmospheres and envelopes of Be stars (including shell stars), Of stars and Wolf-Rayet stars and the motions therein.

d) Binary stars: In many close binary systems, particularly those containing early-type stars, there is evidence of streams of gas enveloping one or both stars. A considerable body of literature exists on this subject. Such streams of gas may be related to the evolutionary progress of stars and to problems of mass loss. A brief, qualitative summary of some of this work has been given by STRUVE (1958). Further observations of the changing velocity field associated with some peculiar systems are summarized by MERRILL (1958). The velocity fields and density of gas shown by these objects are not unlike the velocity fields and density occurring in the extensive atmospheres surrounding supergiants and some main-sequence stars.

4. – Summary of results and interpretation.

(i) The largest velocities are observed in the atmospheres surrounding the hottest objects. Thus the widest spectral lines reported here are for the WN6 object H.D. 192163, the average velocity of the atoms being in the

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neighbourhood of 1 000 km/s. This star also exhibits the largest outflow velocity that was observed, namely — 1 400 km/s. The radial velocity fluctuations have a larger range on the average, *viz.* 30 km/s in the early-type supergiants than in the later-type supergiants where the range is 4 to 8 km/s.

(ii) It appears that given two objects of approximately the same temperature (as determined from the radiation field), larger turbulent velocities are observed for the object with the more extensive atmosphere. Thus atmospheric velocities are greater in the atmospheres of supergiants than in the atmospheres of giant stars or of dwarf stars. Still larger velocities are observed in the shells around some early-type main-sequence stars than in the less extensive atmospheres of the early-type supergiants.

(iii) There is ample evidence that the velocity fields of stellar atmospheres are irregular. The velocity distribution changes from place to place in the stellar atmosphere, witness the multiple chromospheric Ca II *K* lines in *31 Cygni* and in *VV Cephei*. It also changes from time to time, witness the changes of shape of lines in the spectra of extremely luminous stars such as *ε Aurigae*, and the irregular variations of the radial velocity of supergiants.

(iv) Much of the material in extended atmospheres appears to be moving in random directions. However, on the whole there is also evidence that a low density shell of gas is streaming from most stars. The expanding circumstellar shells in the late-type supergiants appear to be moving outwards with respect to the stellar surface at speeds of 10 to 20 km/s. In the Wolf-Rayet stars the most probable outward velocity is greater than 1 000 km/s. The symmetrical wings of the H_α emission profile in Be and shell stars may be explained by a shell expanding with a velocity of several hundred km/s in addition to the turbulent velocity field made visible by the absorption lines. The changing H_α emission profiles of the B-type supergiants, and in particular the violet displacement of the absorption cores also indicate predominantly outward motion.

(v) In view of the simplifications in physical theory that are made in the theory of the curve of growth so as to obtain representations of the situation that may be handled by relatively simple mathematical methods, it is difficult to decide exactly what the so-called microscopic turbulent velocities mean. Certainly they can represent only a small part of the velocity field that exists, for the Doppler shifts due to large velocities effectively change the wave-length of the spectral line sufficiently that so far as the curve of growth is concerned the atoms with large velocities do not contribute to the absorption line at all. The observable quantities used to obtain information about large scale motions in stellar atmospheres, on the whole, reflect prop-

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erties of the atmosphere at high levels, far from the stellar photosphere. The equivalent widths used to form curves of growth, on the other hand, reflect the properties of intermediate and deep layers of the atmosphere. Thus the results summarized as « microscopic turbulence » refer to a different part of the atmosphere, on the average, than do those summarized as « macroscopic turbulence ».

(vi) It has several times been noted that if one observes only the profiles of spectral lines of giants and supergiants in the blue-violet region at a dispersion of about 10 Å/mm, one cannot decide between rotation as the dominant means of broadening and a symmetrical macroturbulence. SLETTEBAK (1956) and ABT (1958), in particular, have favoured the hypothesis of slow rotation. In fact ABT has attempted to work back from the magnitude of this « rotation » to find the point on the main sequence from which the stars now observed as supergiants may have originated. I see no reason compelling one to accept this line of thought. Rather I believe that the observed broadened profiles of the supergiants are due chiefly to large scale, randomly directed motions of the gases in the outer layers of these stars. The principle facts supporting this conclusion are (1) the randomly occurring changes of line shape which are observed for the most luminous stars when their spectra are observed at very high dispersion, and (2) the irregular radial velocity fluctuations found for all supergiants that have been observed in detail. HUANG and STRUVE (1954) also came to the same conclusion on statistical grounds.

It is clear that most, if not all, early-type main-sequence stars rotate rapidly. It is far from clear whether the less numerous early-type stars having luminosities distinctly brighter than the main sequence (that is, the I*b* and I*a* supergiants) rotate at all. It is certain that large scale motions exist in the atmospheres of these stars.

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