14. INSTABILITY IN STARS OF EARLY SPECTRAL TYPE

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This paper consists of two parts which, at first sight, are quite detached from each other: the pulsating variables of spectral types B to F, and the close spectroscopic binaries of the types of β Lyrae, UX Monocerotis and

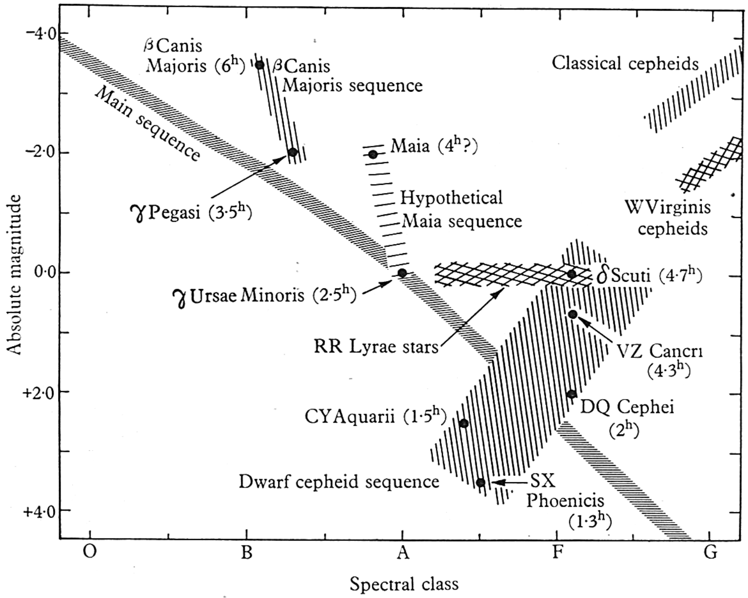

Fig. 1. The sequence of pulsating stars in an absolute magnitude *versus* spectral class diagram.

U Cephei. I shall show that there exists a connexion between these groups which, though still rather nebulous (in both senses of this word), promises to yield interesting results.

Fig. 1 shows the various sequences of pulsating stars with which we have been concerned in recent years at Berkeley. The sequence of the β Canis Majoris stars has been explored in great detail. There is a pronounced period-luminosity relation and also a period-spectrum relation. We are at present working on two stars of spectral type B3 which have even shorter periods than γ Pegasi, but the final conclusions are not yet available;

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one, 53 Piscium, may vary in light with $P \approx 2\frac{1}{2}$ hours, according to A. D. Williams, and in velocity with $K \approx 10$ km./sec., according to R. T. Mathews.

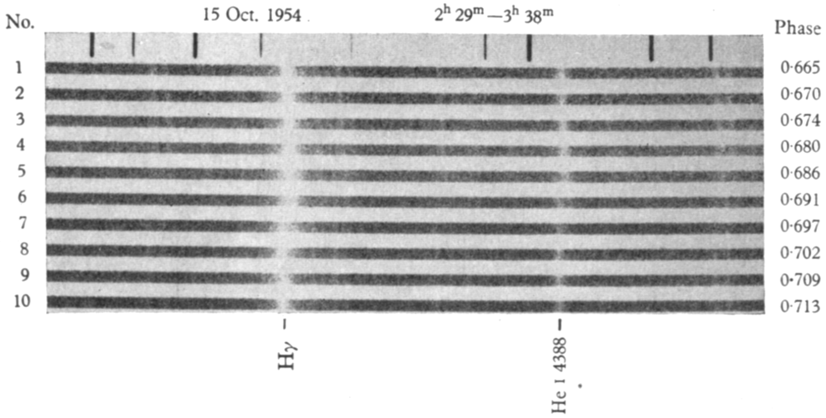

Fig. 2*a*. Spectra of BW Vulpeculae in the λλ 4460–4585 region, obtained by A. J. Deutsch. The phases in the margin correspond to the horizontal scale of Fig. 3.

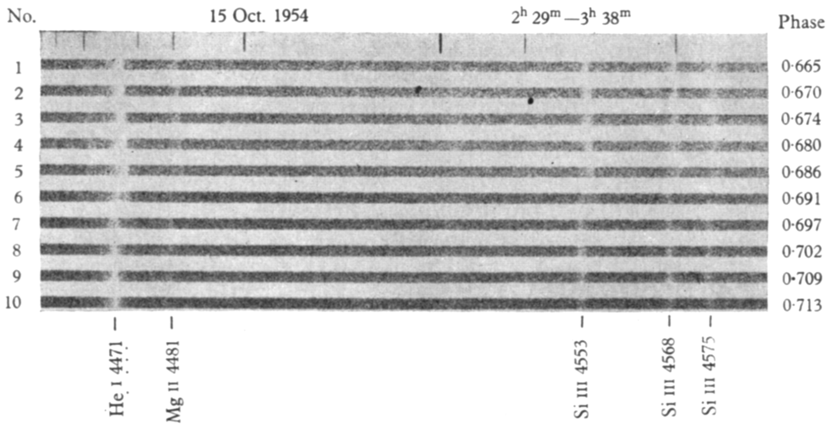

Fig. 2*b*. Spectra of BW Vulpeculae in the λλ 4300–4425 region, obtained by A. J. Deutsch. The phases in the margin correspond to the horizontal scale of Fig. 3.

The most interesting result pertains to the discontinuity of the velocity curves of BW Vulpeculae, σ Scorpii, 12 (DD) Lacertae, and other members of this sequence. It is almost certainly a universal phenomenon. Fig. 2 shows several spectra of BW Vulpeculae, obtained by A. J. Deutsch with the 200-inch telescope. They show the duplicities of the absorption lines much better than my own spectrograms of this star which were obtained in September 1954 at Mount Wilson. Notice that all lines split into components, but that there is a slight delay in Hγ, as compared to He I λ 4472 and the lines of Si III. On the sixth (from the top) exposure the violet component of He I and Si III is already the stronger, while on the same exposure the red component of Hγ is still the stronger of the two. I have referred to this delay as the 'Van Hoof effect', since it was discovered by Dr A. Van Hoof. Fig. 3 shows the velocity curve of

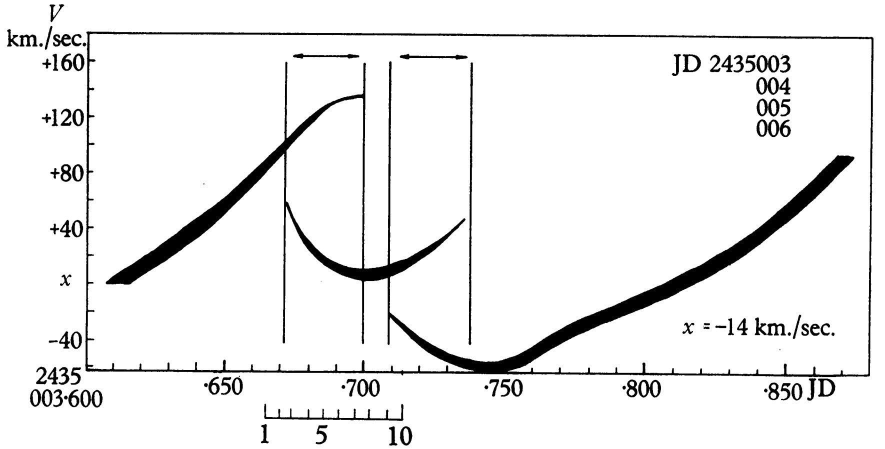

Fig. 3. The velocity curve of BW Vulpeculae. The phases of the spectrograms reproduced in Figs. 2*a* and 2*b* are indicated by the scale at the bottom. The origin of the velocity ordinates, *x*, corresponds to − 14 km./sec.

BW Vulpeculae, of $P = 4^{h}\ 49^{m}$. The character of the discontinuity is not the same as in RR Lyrae and W Virginis, but its theoretical implication is probably similar. Notice that the β Canis Majoris stars are members of population I.

It is reasonable to say that what we observe in these stars are strictly periodic puffs of gas whose velocities are decelerated by gravity, which causes the gases to fall back upon the surfaces of the stars. We have, then, on a very small scale, something in the nature of nova explosions. For further details, I refer to the work of G. J. Odgers at Victoria.

We are, at the present time, engaged in the study of several stars of the δ Scuti sequence, especially HD 199908. These stars resemble in many ways the β Canis Majoris variables, but they also resemble the classical RR Lyrae or cluster-type variables. In all three sequences we frequently find pronounced beat phenomena. Delta Scuti shows a broadening of its absorption lines on the descending branch of the velocity curve. This may mean that its velocity curve would also be discontinuous if we could resolve the components, but intrinsic broadening by turbulence or rotation prevents us from doing this.

The sequence of Maia is quite uncertain and we shall not be able to explore it in the near future.

I now turn to the binaries. The connecting link between them and the pulsating variables is provided by three recent investigations made by my colleagues at Berkeley. The first is a study of UX Monocerotis by C. R. Lynds who has shown that the smaller, A-type, component of this binary of 6-day period is an intrinsic variable having some of the characteristics of the cluster-type stars. The second is a study of AE Aquarii by J. A. Crawford and R. P. Kraft, which attributes the nova-like outbursts of its small, hot component to the capture of gas expelled through the inner Lagrangian point by its large K-type companion. And the third is a theoretical discussion by S. S. Huang of the evolutionary consequences of loss of mass in close binaries. He suggests that while single stars evolve by way of the cluster-type sequence, the components of close binaries by-pass this stage: they evolve more rapidly and pass through a region of instability which, in the H–R diagram, occupies an area of triangular shape between the post-novae and the RR Lyrae variables. The details of this work will soon be published. It leads to a logical interpretation of the duplicity of Nova Herculis 1934, recently discovered by M. F. Walker.

Because of the importance of this problem I have recently started, in collaboration with J. Sahade, a new study of the spectrum of β Lyrae. Figs. 4*a* to 4*f* show the cyclic variations of the spectrum in its 12·9-day period for two regions of the spectrum (near the K line of Ca II, near Hγ, and near He I λ 4472). One set of plates was lined up for the lines of the B9 star, while the other was adjusted by means of the interstellar lines H and K. The phases are shown as decimal fractions of the period, and the numbers which precede the decimal point identify the cycle. The spectrum at the top, phase 2·6451, was obtained on 9 May 1955, at $8^h\,27^m$ U.T.

This complexity of the variations is very great, and my purpose in presenting this material is to solicit help in interpreting it. In a general way, my earlier interpretation was probably correct, but there are many interesting features which were not seen on the relatively inferior Yerkes plates.

I have time to mention only a few of the more remarkable results of our present work:

(1) The satellite absorption lines are of special interest just before mid-eclipse and immediately after it. The former are narrower than the latter, but the high-dispersion plates show that the former are also broadened by Doppler motions. Their edges correspond, in the mean, to velocities of +140 to +200 km./sec., but these velocities increase as we pass from phase 0·95 to phase 0·98, approximately, and in all probability the range also increases.

(2) It was at first disturbing that the spectrum of these redward satellites appeared to resemble rather closely that of the B9 star. There was no reason to believe that this should be the case. However, we can now definitely state that the spectral class as defined in the conventional manner by these satellites is considerably later than B9. It is more nearly A2: the Ti II lines are definitely enhanced (notice especially Ti II λ 4501 which shows a well-marked satellite but no corresponding B9 component); Ca II is also enhanced but not enough to make the spectral type much later than A2. The stream which gives rise to these satellites probably has a higher degree of ionization and excitation than the invisible atmosphere of the companion star. We can infer only that the spectral type of the latter is later than A2.

(3) There is some suggestion that immediately after the disappearance of the red absorption satellites they are replaced by weak emission components. This is best seen in Si II, Mg II and perhaps Ca II. After mid-eclipse the main mass of this stream is hidden by the companion star. Only a fringe remains visible, but this is not seen projected upon the disc of the B9 star.

(4) The violet absorption satellites are strong and very broad. They appear suddenly right after mid-eclipse and range in velocity between −80 and −360 km./sec., remaining about the same between phases 0·04 and 0·05. But at phase 0·09 and until phase 0·12 they are replaced by fairly strong emission components. Evidently this stream remains projected against the B9 disc until phase 0·09, after which it is seen partly against the space between the two stars, and partly against the disc of the invisible F companion star.

(5) This stream is strong in H and He I, but it also shows lines of N II, Ca II and Fe III (λ 4419·6). There seems to be little or no Fe II, Ti II, and strangely no O II. There is probably no He II and no Si III. There is little or no dilution effect: the satellites of He I λ 3888 and λ 3965 are not enhanced, as are the corresponding 'fixed' B5 lines. No doubt this stream is fairly close to the surface of the B9 star, but its ionization is considerably greater, probably because of reduced density and increased temperature.

(6) We conclude that these streams are produced by the instability of *both* component stars near the inner Lagrangian point, a phenomenon which G. P. Kuiper has designated as instability of class A. This agrees with the theoretical results by V. A. Krat, A. N. Dadaev and A. Kranjc. It also permits us to connect the phenomena in β Lyrae with those in U Cephei, U Sagittae, SX Cassiopeiae, UX Monocerotis and many other

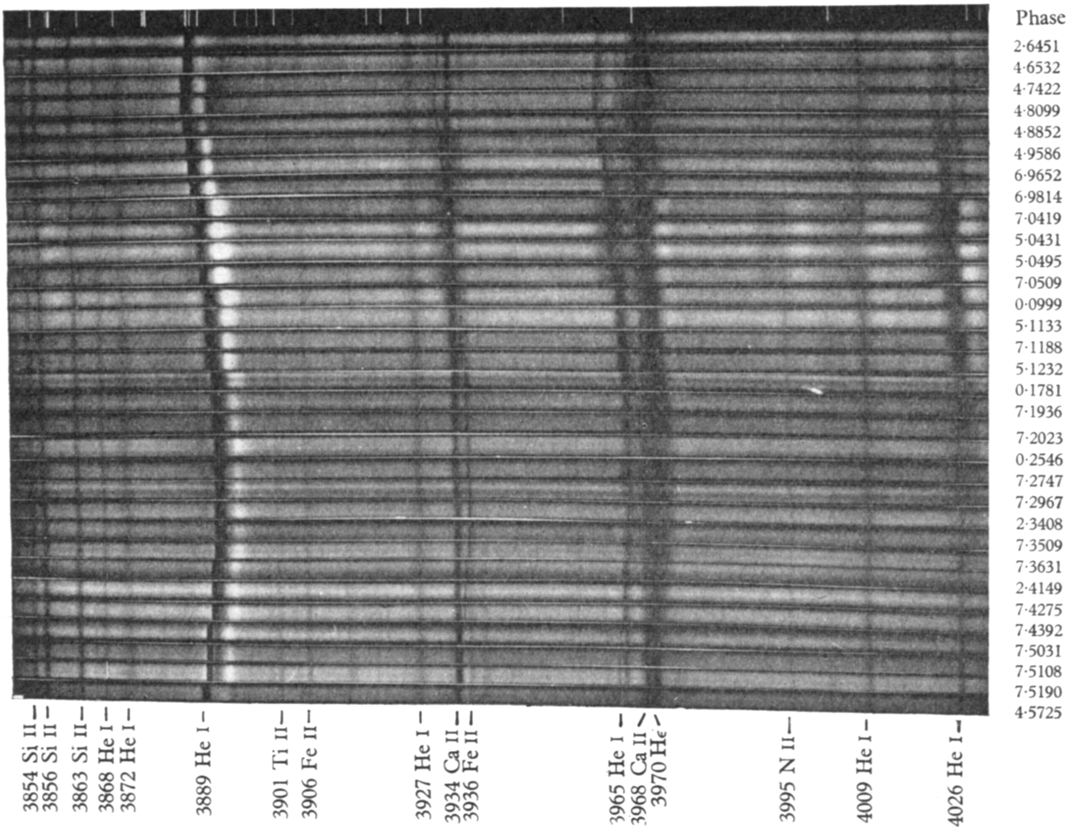

Fig. 4*a*. Spectra of *β* Lyrae in the region λλ 3850–4030. The individual spectra have been shifted so that the features of the B9 component are aligned throughout the series. The phases are in decimal fractions of the period, and the numbers which precede the decimal point identify the cycle.

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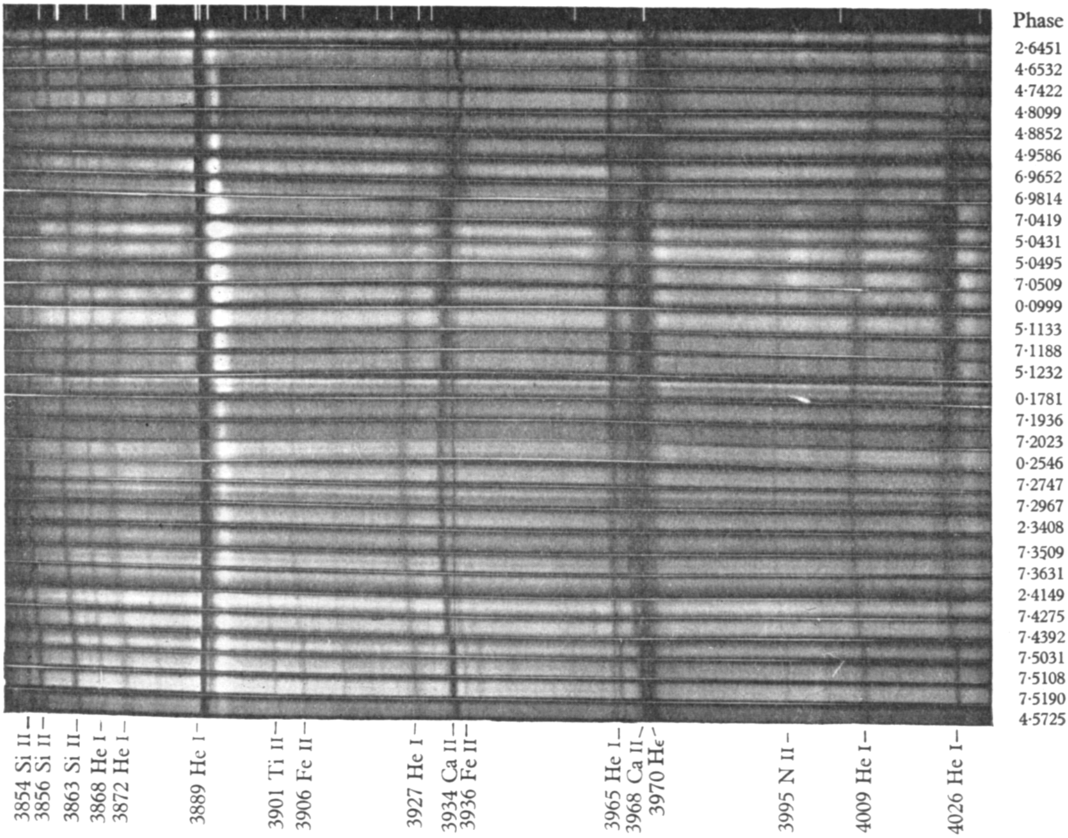

Fig. 4*b*. Spectra of β Lyrae in the region $\lambda\lambda$ 3850–4030. The spectrograms are the same as those used in Fig. 4*a*, except that the alignment has now been made with the aid of the interstellar H and K lines.

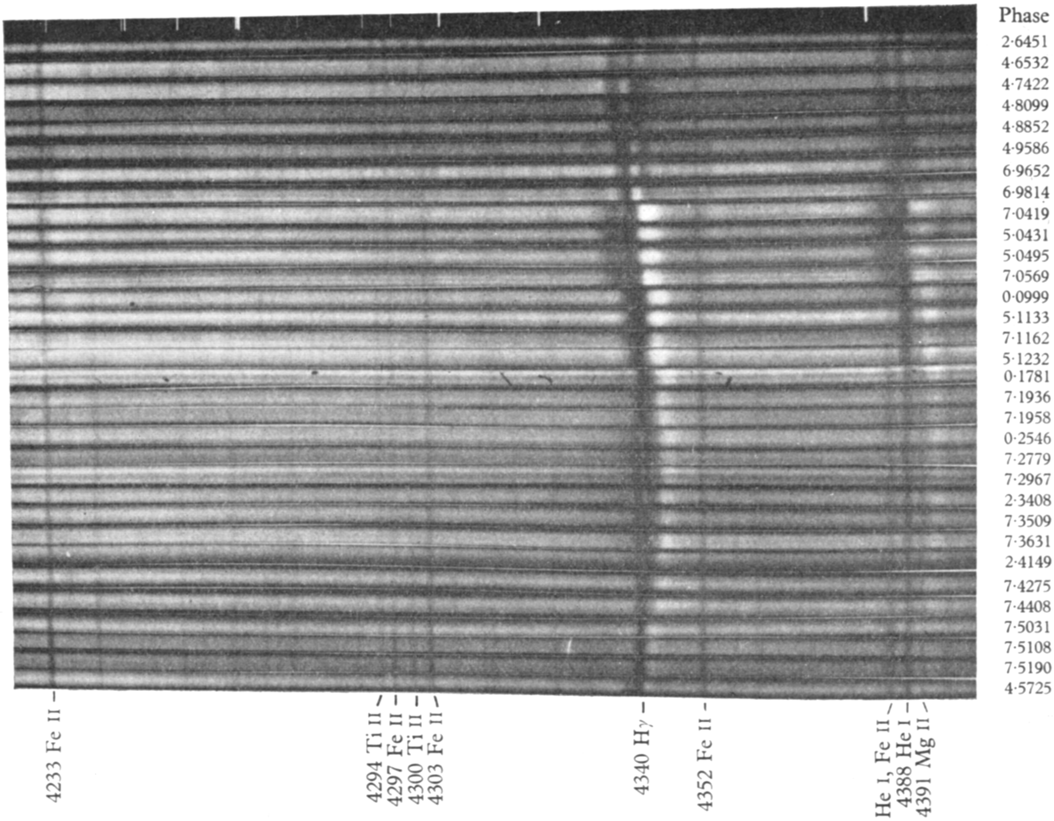

Fig. 4*c*. Spectra of β Lyrae in the region $\lambda\lambda$ 4230–4400. The individual spectra have been shifted so that the features of the B9 component are aligned throughout the series. The phases are in decimal fractions of the period, and the numbers which precede the decimal point identify the cycle.

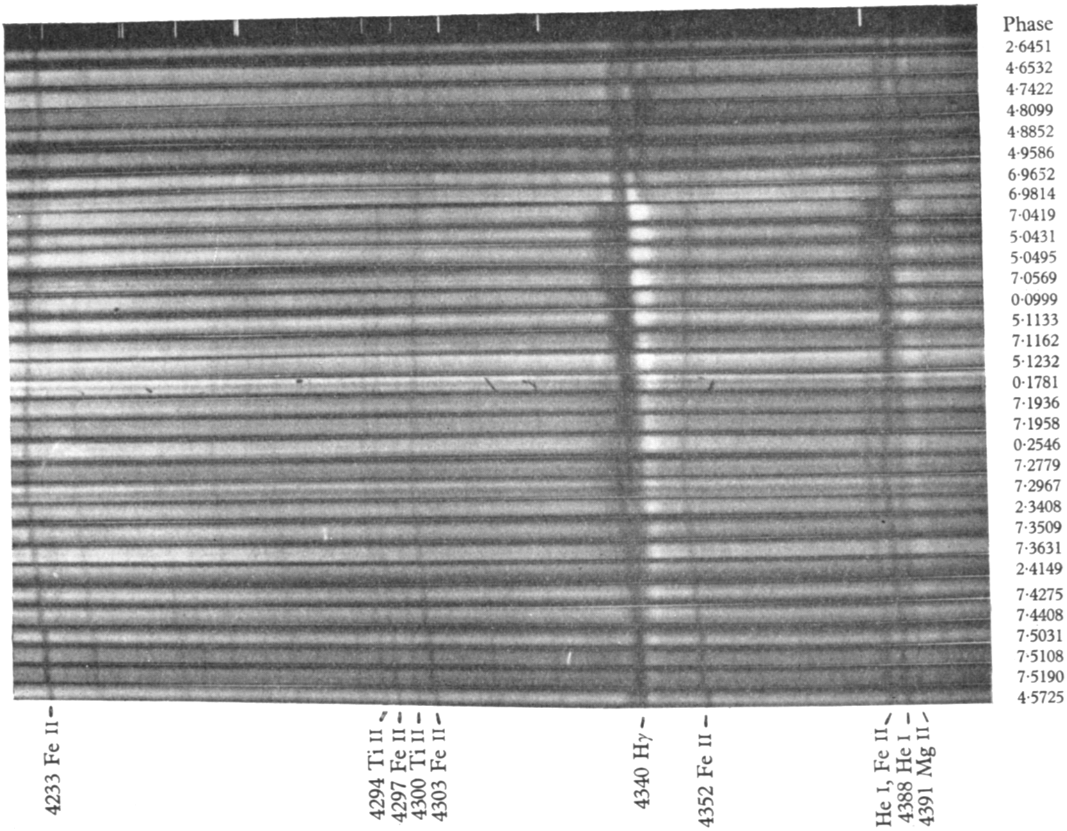

Fig. 4*d*. Spectra of β Lyrae in the region $\lambda\lambda$ 4230–4400. The spectrograms are the same as those used in Fig. 4*c*, except that the alignment has now been made with the aid of the interstellar H and K lines.

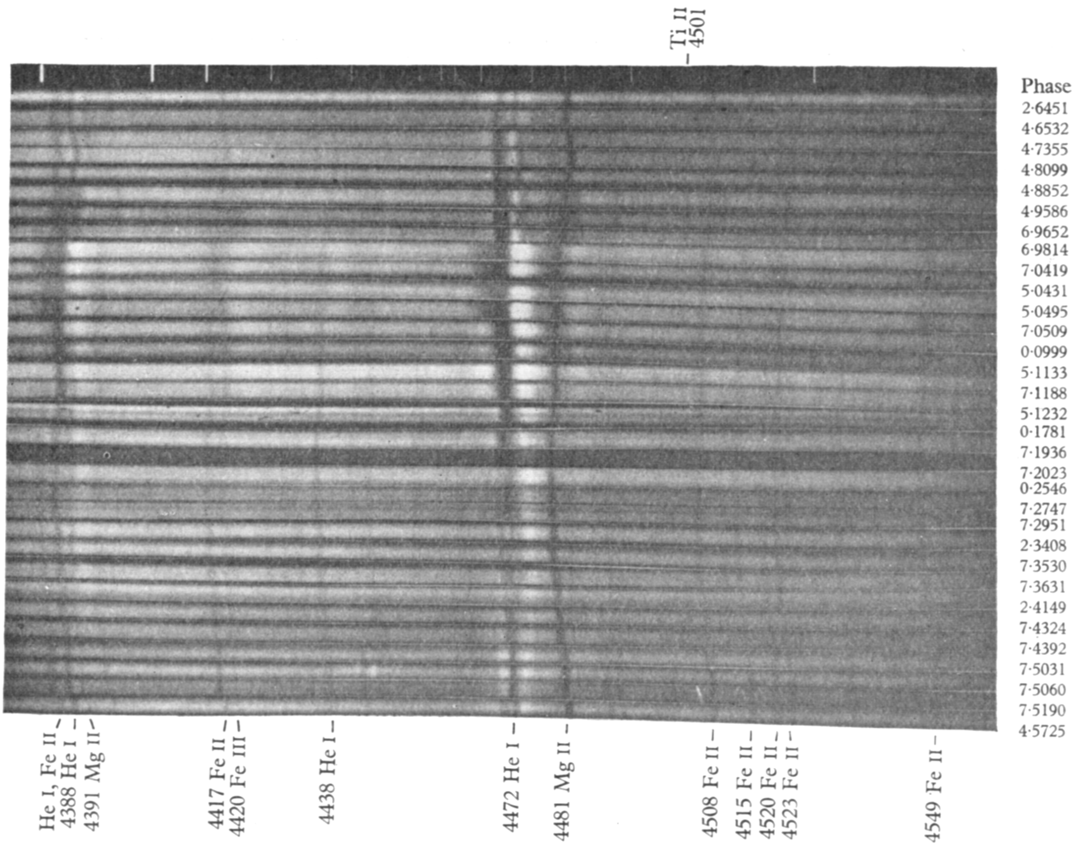

Fig. 4*e*. Spectra of β Lyrae in the region $\lambda\lambda$ 4380–4560. The individual spectra have been shifted so that the features of the B9 component are aligned throughout the series. The phases are in decimal fractions of the period, and the numbers which precede the decimal point identify the cycle.

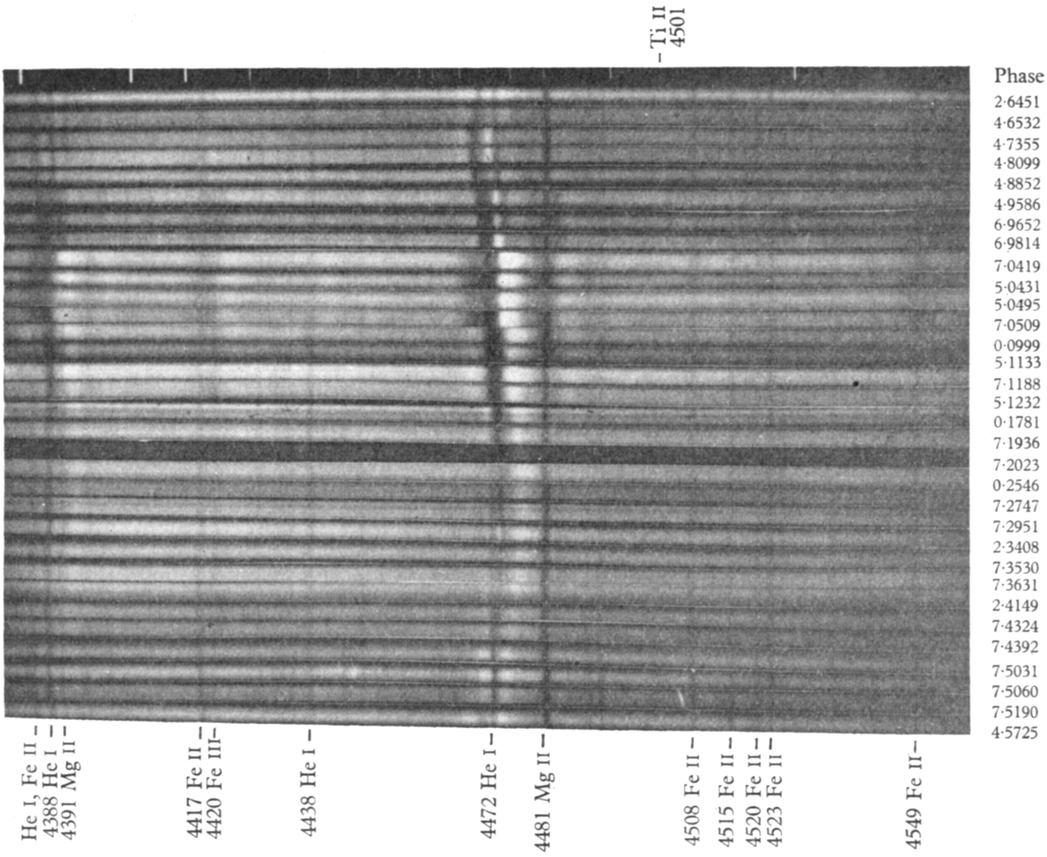

Fig. 4*f*. Spectra of *β* Lyrae in the region λλ 4380–4560. The spectrograms are the same as those used in Fig. 4*e*, except that the alignment has now been made with the aid of the interstellar H and K lines.

close binaries. Evidently this type of instability occurs always when one component star (or both) is spilling over its critical zero-velocity equipotential surface containing the Lagrangian point L_1. It does not matter which component has the larger mass.

(7) In our interpretation of the emission and absorption lines of β Lyrae we must remember that they are not necessarily, and not even usually, produced in the same layers of gas. The importance of this point was brought to my attention twenty years ago by the late B. P. Gerasimovič. Let us consider first the broad emission feature of He I λ 4472 (the other He I lines, excepting those whose lower levels are metastable, and the H lines behave in a similar manner). This feature is produced not only by the condensation of gas between the Lagrangian point L_1 and the following side of the F star, but also by a large cloud of gas which envelops the entire system. Nevertheless, orbital motion is evident from the curvature of the displacements when the spectra are aligned according to the stationary lines. This curvature is conspicuous between phases 0·0 and 0·5, and it is opposite in sense to that shown by the B9 lines: the main mass of the emitting gas moves in phase with the F star and out of phase with the B9 star. The value of K is roughly 100 km./sec., that of the B9 star is 180 km./sec., and that of the F star is 270 km./sec., if Kuiper's mass ratio $\mathbf{m}_{B9}/\mathbf{m}_F =$ 1·5 is correct. The orbital motion of the main mass of the emitting atoms is in agreement with A. A. Belopolsky's early work of 1892.

(8) This orbital motion is not detectable between phases 0·5 and 0·0 because during the second half of the cycle the main mass of the emitting gas is hidden by the two stellar discs.

(9) The B5 absorption lines undergo large and erratic changes in intensity, structure and radial velocity. My earlier work at the Yerkes Observatory indicated that these lines—always strongly displaced shortward—are displaced less before mid-eclipse than after it. The new observations do not disprove this. J. G. Baker's measurements of He I λ 3888 and λ 3965 also show this effect. Since these lines are produced by the gas which is between us and the B9 disc, they do not indicate the motion of the streams except very close to mid-eclipse. They appear then to be *in phase* with the B9 star, despite their large negative displacements. Evidently the large shell enveloping the system expands and revolves around the entire system; the shell is concentric, not with the B9 star, but with the centre of gravity of the system. I believe that this, too, is compatible with Krat's theory. The observed component of the orbital velocity of the shell is small compared to the orbital motions of the stars and to that of the condensation discussed previously.

(10) One of the most conspicuous features of the emission in He I λ 4472 is the sudden increase in intensity at mid-eclipse. This is not nearly so conspicuous in He I λ 3888 and λ 3965. Evidently the uncovering of the emitting condensation—rich in He I λ 4472 and poor in He I $\lambda\lambda$ 3888, 3965—is responsible for this effect. This is in harmony with the results of paragraph (9).

(11) The lines of He I $\lambda\lambda$ 3888, 3965 are produced mainly in the large shell, but this is more the case for the former line than for the latter. The line He I λ 3888 blocks out almost completely the line Hζ. The intensity of the emission line He I λ 3888 undergoes considerable variation, but part of it is caused by the increased exposure times during the eclipses. After this effect is removed there remains a *small* increase in intensity at mid-eclipse which is, no doubt, the same phenomenon as in He I λ 4472. There is also an asymmetry: the intensity is somewhat lower at phase 0·88 than at phases 0·25 to 0·40. This is qualitatively consistent with the observations of K. Saidov. But, contrary to his results, we find that the emission line is never absent. We cannot at this time venture any comments regarding the mechanism proposed by Saidov to account for the variation. It is not clear to us whether his observations were corrected for the exposure-time effect.

(12) Those B9 lines of Si II, Ca II, Mg II, and Fe II which are not complicated by emission behave in a fairly normal manner. But they are considerably strengthened at secondary minimum, which may be due to the absence of the continuous light of the F star. Measurements of this strengthening should give a determination of L_{B9}/L_F, perhaps even as a function of λ.

(13) During the principal eclipse the B9 lines of N II and He I, which are probably not noticeably complicated by emission, are slightly reduced in intensity, without being strengthened to an equal extent at secondary eclipse. We shall not now attempt to explain the distinction between (12) and (13).

(14) The fainter B9 lines become broad and hazy at certain phases during principal eclipse. One thinks immediately of Rossiter's rotational disturbance. But this effect is small, about $\pm$ 12 km./sec. in radial velocity. Moreover, the equatorial rotational velocity of the B9 star is 40 km./sec., as determined from the profiles observed outside of eclipse. The broadening at mid-eclipse is not the same in different cycles, but it is always more pronounced after mid-eclipse than before, and it seems to produce lines which are about twice as broad as is consistent with the rotation of the B9 star. There is some shading toward the violet, after mid-eclipse, especially in Si II $\lambda\lambda$ 4128, 4132. This is almost certainly an effect of electron scattering

in the highly ionized stream of gas which flows from the B9 star toward the observer. The temperature and electron density are of the right order of magnitude to produce the observed broadening, as S. S. Huang has suggested; and the macroscopic motion of the stream in front of a considerable portion of the B9 disc would, according to Mrs E. Böhm-Vitense, produce a small asymmetry in the line—qualitatively in accordance with the observations.

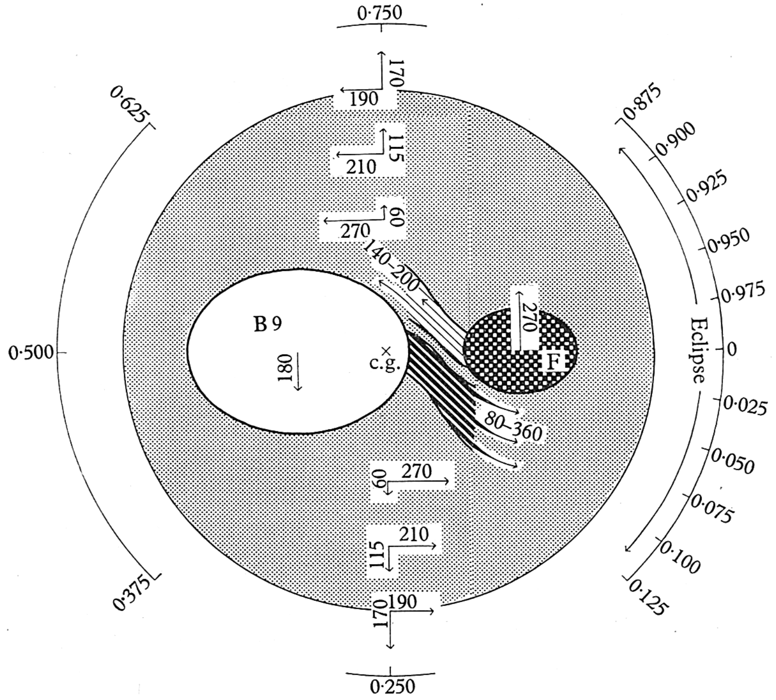

Fig. 5. A model of β Lyrae.

(15) There are similar, but less pronounced irregular changes in the profiles of the same lines (especially Fe II $\lambda\lambda$ 4508, 4515, 4520, 4523, etc.) outside of eclipse. We do not yet know whether these changes affect the radial velocities. They could also be due to electron scattering (or to changes in turbulence) in the large shell.

(16) The puzzle of the rotational velocity of the B9 star remains unsolved. Since $a_1 \sin i = 33 \times 10^6$ km., and $R_1 = 0{\cdot}5\ (a_1 + a_2)$, it is impossible to reconcile the observed velocity with the value of $2\pi R_1/P_{\text{orbit}}$, for which Kopal's elements give 230 km./sec. This difficulty remains even when the mass ratio is quite different from 1·5, as given by Kuiper. If we abandon the mass-luminosity relation for the F star and assume that $\mathbf{m}_1/\mathbf{m}_2 < 1$, the

rotational velocity can be reduced to about 100 km./sec. But it is still greatly in excess of the observed value. Perhaps we must assume that $P_{rot.} > P_{orbit}$. This would be unusual in an eclipsing binary; but, on the other hand, it is known that single super-giants rotate slowly. It may, of course, be that the outer strata rotate more slowly than the inner.

(17) Still another puzzle is that of the luminosity of the B9 star. The spectroscopic criteria, such as the number of H absorption lines and their Stark broadening, suggest $M_{v,1} = -4{\cdot}5$; the mass-luminosity relation for the B9 star would then give $\mathbf{m}_2 = 13\ \mathbf{m}_\odot$. The mass function

$$\mathbf{m}_2 \sin^3 i/(1+\alpha)^2 = 8{\cdot}3\ \mathbf{m}_\odot$$

would give $\mathbf{m}_2 = 21\ \mathbf{m}_\odot$ and $\alpha = \mathbf{m}_1/\mathbf{m}_2 = 0{\cdot}6$. This does not help with the rotational discrepancy of the B9 star, and we do not believe that the result is correct. But it is also difficult to accept Kuiper's compromise solution $M_{v,1} = -7{\cdot}6$ and $\alpha = 1{\cdot}5$, since his other criteria suggest a lower luminosity.

(18) Fig. 5 summarizes the results obtained from the observations. The spectrograms of β Lyrae were obtained by O. Struve and J. Sahade as guest investigators at the Mount Wilson Observatory. All spectrograms, 190 in number, were made with the coudé spectrograph of the 100-inch telescope, using Eastman Process emulsion. The dispersion was 10 Å/mm.