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AN INTERESTING GROUP OF PULSATING STARS

OTTO STRUVE

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On May 14, 1902, Professor Edwin B. Frost, later director of the Yerkes Observatory, made an important discovery, although at the time he himself probably did not realize how deeply it would affect our knowledge of the stars. On that night he took two spectrograms of the bright B-type star β Cephei. During the winter of 1901–1902 he had measured eleven spectrograms of this star and found that it had a variable velocity. He states in his first announcement concerning β Cephei: "We had assumed from the first plates that the period would be rather long, but a suspicion to the contrary led me to take two plates on the night of May 14, and during the interval of five and one-half hours the velocity changed 14 km, or nearly half of the whole range so far observed." Such rapid variations of velocity were quite unheard of in 1902, and Frost diligently continued his observations. Four years later he announced that the period is $4^h\ 34^m\ 11^s$, and that the velocity curve is nearly symmetrical, with a range of 34 km/sec. The shortest period of any spectroscopic binary previously known was 1.45 days in the case of μ^1 Scorpii and V Puppis. Frost noticed that the radius of the orbit of β Cephei, computed from the velocity curve, would be incredibly small—only 45,000 km—and suggested that the binary hypothesis could be true only if the inclination of the orbit were close to 0°. He says: ". . . if the radius of the orbit of the brighter star is assumed for the moment to be the same as that found by Vogel for Algol (1.6 million km), then the inclination of the plane would lack only about 1½° of

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90°; and the observed projected velocity would have to be increased nearly forty-fold, yielding an actual velocity of over 600 km/sec."

Beta Cephei was not then known to vary in light, and this was believed to support the hypothesis of a small inclination. Frost was therefore immensely interested when, in 1913, P. Guthnick announced that the light of β Cephei varies with a range of 0.05 magnitude, the period of this variation being identical with that found by Frost. The light-curve, however, did not resemble those of ordinary eclipsing variables. Furthermore, it seemed inconceivable that the small range of radial velocity could be reconciled with an eclipse. The problem of β Cephei remained unsolved for many years.

Knowing that in order to explain the apparent contradictions in β Cephei more observational material on other stars was required, Frost started systematic observations for the detection of other similar objects. Every star known to have a variable radial velocity for which no period had been found he placed on his observing program and obtained long series of spectrograms of these stars on a few single nights. Most of these cases yielded only constant velocities, but he gradually discovered a small number of stars which seemed to resemble β Cephei. Other observatories added to the list, and by 1921 the number was sufficient for a preliminary discussion. This discussion Mr. Frost assigned to me, a few weeks after my arrival at the Yerkes Observatory.

For spectroscopic binaries of types O, B, and A, the amplitude of the velocity curve increases rapidly, on the average, with decreasing period, in accordance with Kepler's third law. But this increase continues only until a period of about 1.3 days is reached. For still shorter periods the amplitude again decreases. This can mean only one thing: β Cephei and all similar stars are not true binaries. They resemble more closely the Cepheid variables, but differ from them by the small range of their light-variations. Many representatives of this group display irregularities in their light-curves as well as in their velocity curves. The entire group has often been designated as the β Canis Majoris stars, and F. Henroteau, who, I believe, first introduced this term,

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counted β Cephei among them. The name is, however, historically incorrect. Beta Cephei was, without doubt, the first and most typical representative of the mysterious group of quasi-Cepheids of early type and of very short period.

The second member of this group of stars in order of discovery was σ Scorpii. V. M. Slipher announced in 1904 that the radial velocity of this star is variable, but it was not until 1916 that Father Selga determined its period of 5.9 hours.

The third representative was β Canis Majoris, for which S. Albrecht found a variable velocity in 1908 and for which he determined, in 1910, a period of slightly over six hours. Both of these stars, σ Scorpii and β Canis Majoris, were found to vary in light by J. Stebbins, the former in 1916, the latter in 1928.

Finally, in 1912, W. S. Adams noticed that the radial velocity of 12 Lacertae is variable, and in 1915 R. K. Young found its period to be 4.6 hours. This star was also found by Stebbins to vary in light.

These four stars all belong to spectral class B, and it was evident as long ago as 1920 that they form a group of objects distinct from the classical Cepheids. In 1928 Henroteau published a list of 22 stars known or suspected to be members of this group. J. H. Moore in 1936 listed only 13 β Canis Majoris stars, and of these only seven were of spectral class B. Two years later C. P. and S. Gaposchkin in their famous book *Variable Stars* recognized 30 stars, of which 13 were regarded as somewhat unreliable, leaving a total of 17, with only nine belonging to spectral class B. In 1941 O. Struve and P. Swings reviewed the entire status of the problem and concluded that only the four original stars, namely β Cephei, σ Scorpii, β Canis Majoris, and 12 Lacertae, could definitely be recognized as members of a single group of variable stars.

An important advance was made in 1918 by Henroteau when he noticed that the appearance of the spectral lines of β Canis Majoris undergoes periodic changes: "Sometimes the lines are narrower, sometimes wider and more diffuse than the general average condition."

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The period of these changes in line width is $6^h\ 2^m$. This is close to, but not identical with, the period derived from the radial velocities, namely $6^h\ 0^m$, which Henroteau obtained from the material of the Lick Observatory but which he was not able to substantiate from a discussion of several hundred spectrograms secured by him at Ottawa.

Although in the 1920's a large number of investigations were devoted to these stars, the results were rather disappointing. The observations merely showed that the radial velocities and the brightnesses of these stars vary with the same period, and that the periods themselves range between about four hours and six hours.

It was the work of W. F. Meyer which ushered in the modern phase of the investigation of the β Canis Majoris stars. His exhaustive discussion of β Canis Majoris, based on a great number of spectrograms taken during 1930–32 and subsequently at the Lick Observatory, showed conclusively that "the velocity curve can be represented (within the errors of observation) as the *resultant of two sine curves with slightly different amplitudes and periods.*"[1] The values of the two periods found by Meyer were $6^h\ 0^m$ and $6^h\ 2^m$, the latter period being *identical with Henroteau's period for the changes in the appearance of the spectral lines*! Unfortunately, Meyer's work was terminated by his death in 1948. Thereafter J. H. Moore, retired from the directorship of the Lick Observatory, took over the responsibility for completing the discussion of Meyer's material, but he too died before he could complete this task. In an obituary for Dr. Meyer, Moore wrote:

> He became interested in β Canis Majoris whose complex variations in radial velocity arise from causes other than orbital motions, and to which he devoted an extended investigation based upon a long series of observations made in different years. Assuming that the observed velocity curve was the resultant of two velocity curves of different amplitudes and slightly different periods, he was able to derive a formula which satisfactorily represented all observations available to him in 1932, and it appeared that at least the first step had been taken toward a solution of the problem. More recent observations, and in particular those of this last year, indicated further complexities; and it was upon these he was working this past summer.[2]

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Unfortunately, Dr. Moore, who was fully acquainted with Dr. Meyer's ideas, took with him to his grave what he knew of the "further complexities" of β Canis Majoris.

As a Morrison Research Associate at the Lick Observatory in 1950 I undertook to complete the discussion of β Canis Majoris; the results, which fully confirmed Meyer's earlier conclusions, were published in the *Astrophysical Journal*, **112**, 520, 1950. In this article I discussed the radial velocity of β Canis Majoris obtained from 698 three-prism plates secured at the Lick Observatory between 1904 and 1948. The complexity of the results made it clear to me that sporadic observations of the stars of this group yielded little new information. Hence an intensive program of research on these stars was started in Berkeley in 1950 and has been continued until the present time. Most of our efforts have been devoted to the study of the spectra, but an appreciable amount of time also has been devoted to obtaining photoelectric light-curves, for it has become clear that when two periods are simultaneously involved in the velocity variations of one of these stars, the same two periods are also, in general, involved in the light-variations. The spectra, now numbering about 3000, have been taken at the Mount Wilson Observatory, with the coudé spectrograph of the 100-inch telescope and the cassegrain spectrograph of the 60-inch telescope, and at the Lick Observatory with the Mills spectrograph of the 36-inch telescope. The photoelectric observations have been made at the Lick Observatory with the Crossley reflector and the 12-inch refractor.[3]

In this work the following Berkeley astronomers have participated, in addition to the present writer: S. S. Huang, R. P. Kraft, S. M. Kung, R. D. Levée, D. H. McNamara, M. F. Walker, A. D. Williams, and V. Zebergs. We have also had the co-operation of several visiting scientists from other institutions, notably A. van Hoof and F. C. Bertiau. Parallel with our own investigations, important spectrographic results have been obtained at the Dominion Astrophysical Observatory, Victoria, B.C., by R. M. Petrie and G. J. Odgers. Photoelectric observations have been secured at several observatories, especially at Utrecht by C. de Jager and at Mount Stromlo, near Canberra, Australia, by A. R. Hogg. An important advance in the interpretation of the

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complicated velocity and light-variations of ν Eridani was made by V. Zessevich in the Soviet Union. On the theoretical side, the most significant recent contribution has come from the pen of P. Ledoux of Liége, Belgium.

At the present time, ten stars are definitely known to be variables of the β Canis Majoris type and half a dozen other stars are suspected of being members of the group. A list of the ten recognized members is given in Table I. In this table we have listed the period or periods of the velocity and light-variation of each star, the total ranges in radial velocity for each period, the greatest ranges in brightness, the spectral type together with its luminosity class, the color of the star in terms of the quantity $B - V$, and, finally, the visual absolute magnitude.

The stars have been arranged in order of decreasing period. The first star has a period of about six hours, the last of about three and one-half hours.

We notice that half of the stars show two periods, while the other half appear to have only a single period. In two of the stars showing only a single period, however, the velocity and light-range are none the less variable. The shortest periods of the table are single, but among the longer periods we encounter at least two stars, BW Vulpeculae and δ Ceti, also having single periods. Nor is there any clear-cut relation between the periods and the ranges in radial velocity and in brightness. It may be significant that the two stars having the shortest periods are associated with very small ranges; but the largest ranges in velocity and in light occur in BW Vulpeculae, whose period is considerably shorter than those of β Canis Majoris and of σ Scorpii.

The table shows a most remarkable correlation between the period, on the one hand, and the absolute magnitude and the color on the other. The best way to illustrate this relation is in the form of a color–absolute magnitude diagram, shown in Figure 1, mainly from the work of McNamara and Williams. The spectral types corresponding to the color scale are also indicated. The sequence of the β Canis Majoris stars appears to start at the top with a spectral type slightly earlier than B1 and with a visual absolute magnitude of about −4.5. The sequence is at first nearly vertical until near absolute magnitude −4.0 it shifts toward the right, and

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near spectral class B2 and absolute magnitude —2.8 it merges with the main sequence.

Are all stars in the shaded region of the diagram members of this group? We do not yet know the answer. Our efforts to discover new members have been, on the whole, disappointing, but our search was not limited to the shaded region of the diagram since the exact spectral types and absolute magnitudes of the B-type stars are not sufficiently well known. Nor can we answer the following question: Does the sequence abruptly cease at the upper and at the lower ends? We have now under observation two suspicious stars of type B3, namely 23 Sextantis and 53 Piscium. Williams has tentatively suggested that the period of the former may be three hours and that of the latter about two hours. There are some slight indications that the radial velocities of these two stars are also variable, but we do not as yet know the ranges, or even the exact spectral types.

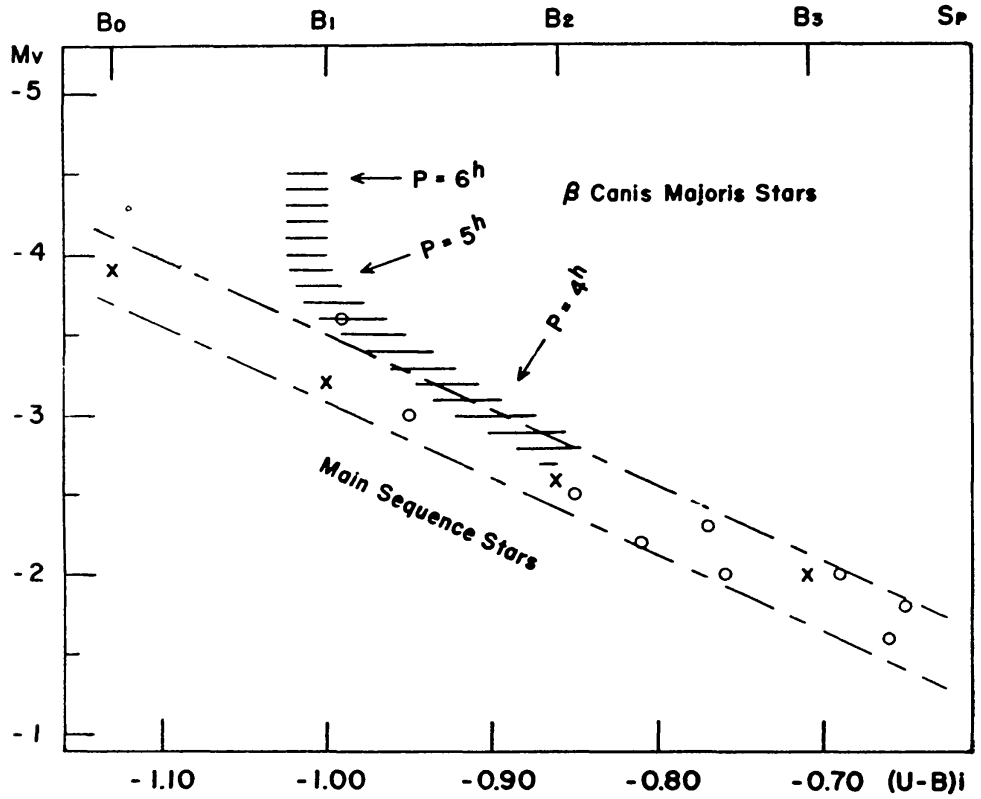


FIG. 1.—The sequence of the β Canis Majoris stars in the color–absolute magnitude diagram. The open circles and crosses represent individual normal stars belonging to the main sequence.

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At the upper end of the sequence the stars belong to Morgan's luminosity class II-III. In this region of the diagram we begin to encounter stars with turbulent atmospheres. It is probable that among the stars of the β Canis Majoris type are objects with variable radial velocity and perhaps variable brightness of the kind found among the supergiants such as α Cygni and ε Aurigae. A possible candidate would be ρ Leonis, but it may be very difficult to distinguish between a true member of our sequence and an irregular variable of the supergiant variety.

We have already seen that five of the ten members of our group have interfering periods which in the case of β Canis Majoris differ by only two minutes. The resulting beat period is slightly more than 49 days. This is the longest beat period in the group. The others run all the way down to about seven days.

Figure 2 illustrates the beat phenomenon in the radial-velocity variation of ν Eridani. The principal period is $4^h\ 10^m$ and the associated range is 49.0 km/sec. The interfering period is $4^h\ 16^m$ and its associated range is 22.0 km/sec. The beat period is therefore about seven days, and the maximum range 71.0 km/sec, while the minimum range is 27.0 km/sec. The beat phenomenon in the light-curve would give almost the same picture: $\Delta m_2 = 0.114$ mag., and $\Delta m_1 = 0.067$ mag. Hence, the maximum range in brightness is 0.181 magnitude and the minimum 0.047 magnitude. But the individual cycles of the light-curve would all be slightly displaced: maximum brightness occurs when the radial velocity is zero, on the descending branch of each velocity cycle.

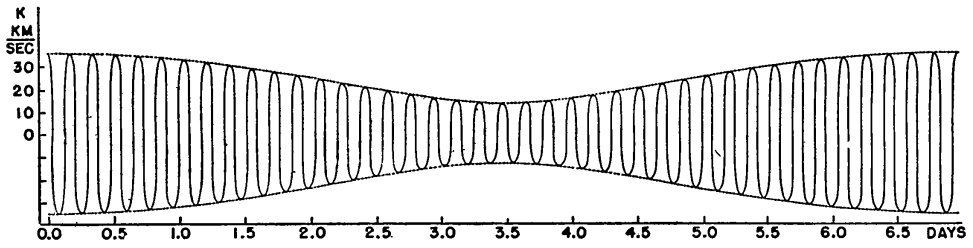


FIG. 2.—The beat phenomenon in the velocity curve of ν Eridani.

However, the ratio $2K_2/2K_1$ is not always the same as $\Delta m_2/\Delta m_1$. Thus in the case of 16 Lacertae the former is 3.3, while the latter is only 1.6. Nevertheless there is a correlation between $2K$ and Δm, as is seen in Figure 3, in which the corre-

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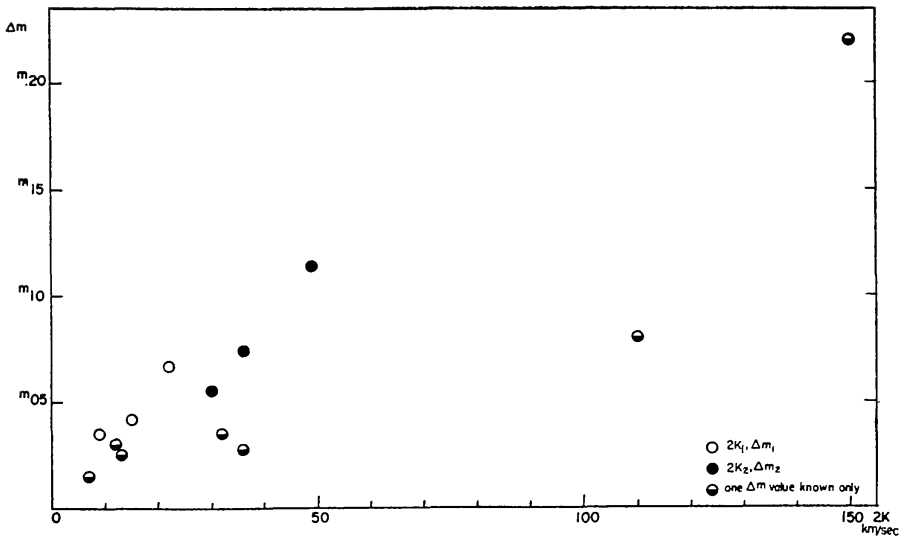


FIG. 3.—The correlation between ranges in radial velocity and in brightness in the β Canis Majoris stars.

sponding values are plotted. While the scatter is large, this correlation seems to apply to both interfering oscillations.

There is also a correlation of $2K$ and Δm for any one star in which these quantities are variable. Such a correlation must obviously exist when both quantities are affected by the same beat phenomenon. But in most stars there are irregular changes in addition to those produced by the interference of the two harmonic oscillations. It is probable that the correlation extends to these fluctuations as well.

For 12 Lacertae, De Jager has resolved the two oscillations of the light-curve and the velocity curve, as is shown in Figure 4. For both oscillations maximum brightness occurs halfway on the descending branch of the velocity curve.

For all those cases in which photoelectric colors have been determined, the stars are slightly bluer at maximum than at minimum brightness. Thus, in the case of 16 Lacertae, the temperature at maximum light may be about 1000° K higher than at minimum light. Although this would imply a change in spectral type, the appearance of the absorption lines is not sufficiently pronounced to verify this change in 16 Lacertae. In BW Vulpeculae, however, there is a marked strengthening of the lines $H\gamma$ and $H\delta$ at minimum brightness. This is probably caused in part by a small

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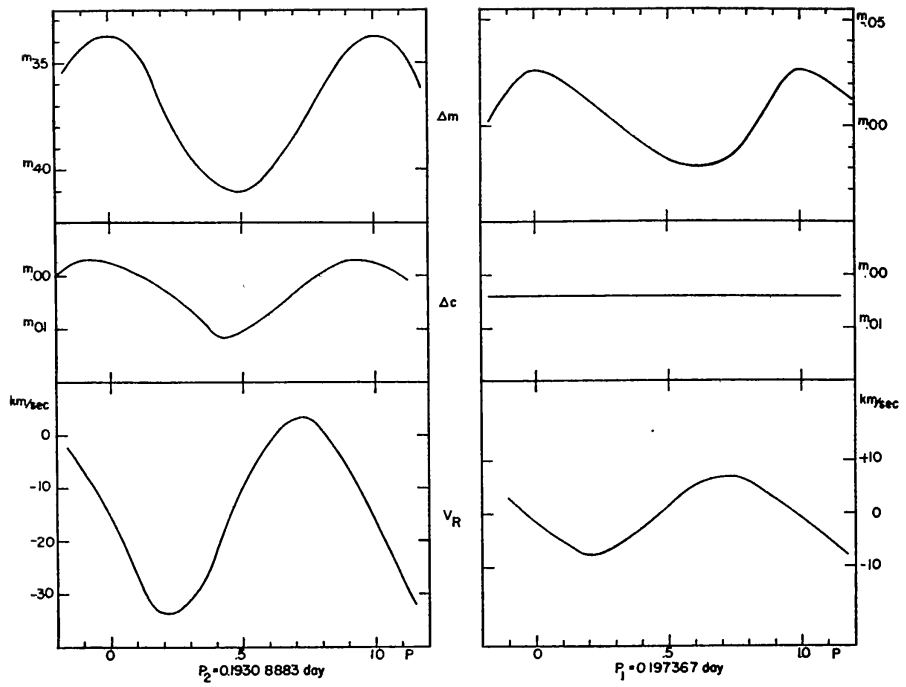


FIG. 4.—Decomposition of the light-curve and velocity curve of 12 Lacertae by De Jager.

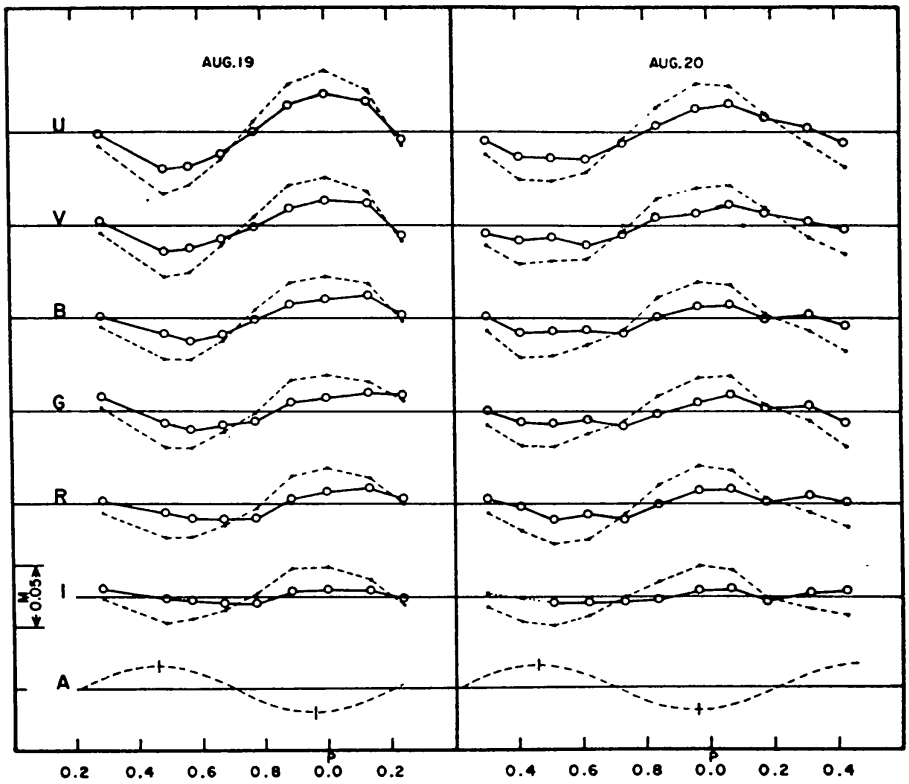


FIG. 5.—Six-color observations (open circles) of β Cephei by Stebbins and Kron. The significance of the dashed curves is discussed in the text.

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change in temperature, the stronger lines indicating a slightly more advanced spectral type. The hydrogen lines are also sensitive to absolute magnitude, and at minimum brightness the star has its greatest diameter, and, consequently, its smallest atmospheric pressure.

The lines $H\alpha$ and $H\beta$ fail to show the strengthening at minimum brightness. Instead, they are greatly reduced in equivalent width. The Victoria astronomers attribute this to incipient hydrogen emission which fills in the absorption lines. This is reminiscent of the discovery of a similar weakening in $H\alpha$ of β Cephei, announced many years ago at the Lick Observatory.

The observed variation in the brightness of any radially pulsating star is the result of two effects: a change in the radius of the star and a change in its temperature. Can we separate these two effects? The most comprehensive study of this sort was made in 1954 by J. Stebbins and G. E. Kron at the Lick Observatory. They observed β Cephei on two nights in six colors, ultraviolet, violet, blue, green, red, and infrared. The resulting continuous curves, shown in Figure 5, demonstrate the relation between Δm and wave length; the star is also seen to be bluer at maximum brightness. They also show a small but unmistakable time lag in the epochs of maximum and minimum brightness as we pass from ultraviolet to infrared light. A similar lag was previously found by Stebbins in η Aquilae and δ Cephei.

At the bottom of Figure 5, the curve A represents the change in brightness caused solely by the change in the size of the star. This curve results from the integration of the radial-velocity curve. When we subtract the curve A from each of the observed light-curves, we obtain for each night the six dashed curves which are the true radiation curves: they result solely from the changes in temperature. These curves are now *in phase*, and their amplitudes are consistent with Planck's law when the average temperature of the star is 23,000° K.

This agreement is obtained only when the change in radius $\Delta R = 5.24 \times 10^4$ km $= 0.075 R_\odot$ and at the same time the range of the curve A is 0.036 magnitude. This combination of the two values requires that $R = 9.0 R_\odot$. At a temperature of 23,000° K, β Cephei would then have a visual absolute magnitude of $M_v =$

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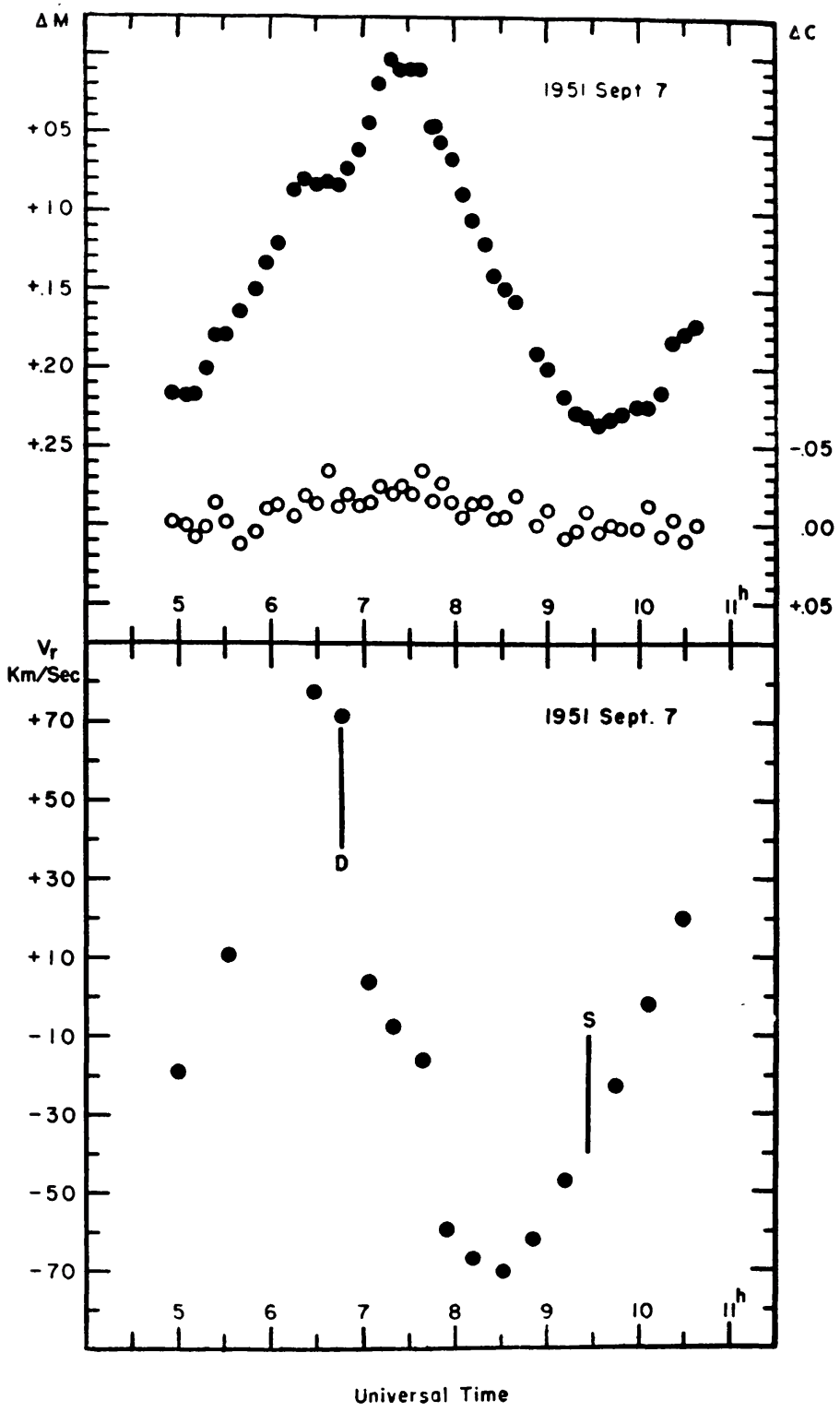


FIG. 6.—Light-curve, color curve, and velocity curve of BW Vulpeculae by Walker. The letters *D* and *S* refer to the times when the spectral lines appear most diffuse or sharpest on the relatively low-resolution spectrograms obtained in 1951.

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—4.2. W. W. Morgan and P. C. Keenan in 1951 obtained the value —4.1 from the spectrum. The conclusion seems warranted that "the variations of this star are satisfactorily explained on the pulsation theory."

Stebbins and Kron have stressed the fact that β Cephei is a relatively simple variable star; it has only one period and does not show changes in the line profiles. Does the test of the pulsation hypothesis apply also to those members of the group which have interfering oscillations or show changes in their line profiles? The answer is no. M. Walker has used a modification of the test proposed in 1946 by A. J. Wesselink for ordinary Cepheids. The result was wholly negative in the case of BW Vulpeculae: "the entire light-variation can be explained as a result of a change in the temperature of the star."

In the case of 16 Lacertae, Walker even arrived at the bizarre result that to account for the light variation it is necessary to postulate a radius of *minus* $50R_\odot$! Walker concludes: "The observations, if they mean anything at all, might be taken as strengthening the supposition that the stars BW Vulpeculae and 16 Lacertae undergo some sort of non-radial pulsation."

The foregoing discussion of the pulsation hypothesis was based upon the assumption that the star's photosphere oscillates back and forth with a small amplitude, overshooting the normal radius by a small amount in each direction. It carries the reversing layer with it, so that at each instant the Doppler shift of the absorption lines gives an accurate determination of the velocity of expansion or contraction of the photosphere. There is at present no reason to question this assumption in the case of β Cephei, ξ^1 Canis Majoris, γ Pegasi, and δ Ceti. All of these stars have single periods and sharp spectral lines at all phases. Their velocity curves and light-curves are very nearly sine curves.

There is no such simplicity in the other six members of our group. Their light-curves often show peculiar disturbances, such as the "standstill" on the ascending branch of that of BW Vulpeculae, shown in Figure 6. Similarly, the velocity curve of this star shows a "standstill" on the descending branch. The recently found interpretation of this curious velocity curve is shown in Figure 7. The absorption lines actually *become double* in two in-

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tervals: at phases .670–.700 and .710–.740 day of Figure 7. This duplicity of the lines gives the impression, on spectrograms taken with insufficient resolution, of line diffuseness.

Plate I shows a series of successive spectrograms of BW Vulpeculae obtained by A. J. Deutsch with the 200-inch telescope. The phases of his ten exposures are indicated by the arrows in Figure 7. It should be remembered that the discon-

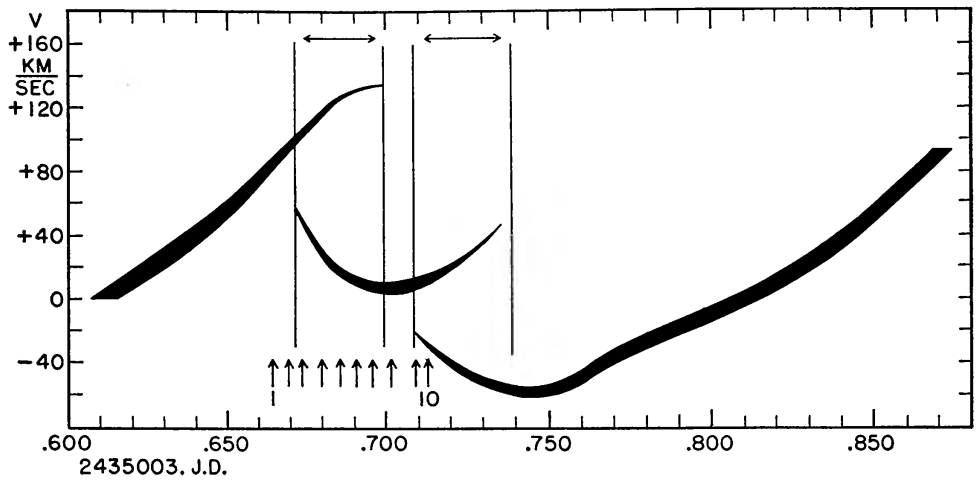


FIG. 7.—The discontinuous velocity curve of BW Vulpeculae from observations on four days beginning with JD 2435003. On the velocity scale, 0 = —14 km/sec. The short vertical arrows, 1–10, indicate the phases of the ten spectrograms in Plate I.

tinuous velocity curves of Figure 7 were obtained from several cycles on JD 2435003–2435006, while the spectrograms taken by Deutsch were obtained on JD 2435030. Nevertheless they show essentially the same phenomenon: the lines split into components which rapidly change in intensity. The red-displaced component fades out at phase .697, while the violet (intermediate) component makes its first appearance at phase .674 and reaches maximum strength at phase .709. At phase .713 a new violet-displaced component is just emerging. This component would gradually increase in intensity and would account for the long ascending branch of the velocity curve. There are thus actually three distinct components of each line involved, but only two are seen simultaneously.

Because of the importance of this phenomenon, we show in

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Plate II the duplicity of the *Si* III lines in 12 Lacertae and in Figure 8 the corresponding discontinuous velocity curve. In this

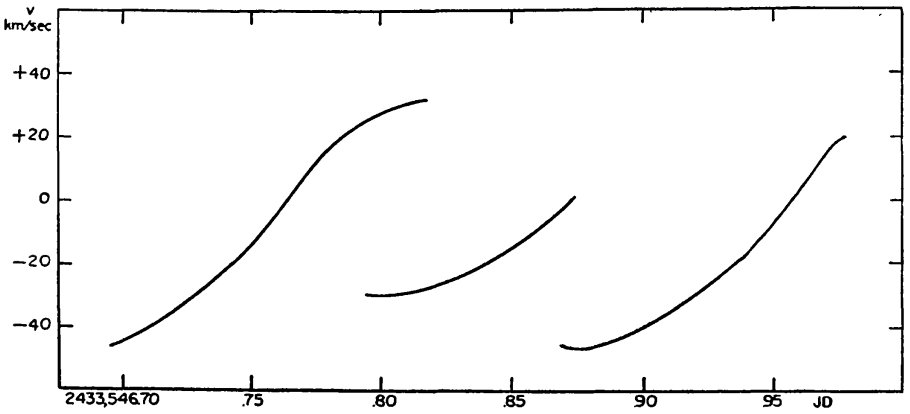


FIG. 8.—The discontinuous velocity curve of 12 Lacertae.

star the discontinuity is seen only when $2K$ is large, that is, when $2K_1$ and $2K_2$ are *in phase* and thus augment each other in the beat curve.

Essentially the same effect is present also in σ Scorpii. In all three stars the hydrogen and helium lines lag a few minutes behind the lines of *Si* III and *O* II in reaching the corresponding ratio of intensity of the two components. I have referred to this phenomenon as the Van Hoof effect because it was first observed by A. van Hoof in β Canis Majoris and 16 Lacertae, despite the fact that in these two stars the duplicities have not as yet been observed. The lag appears in these stars as a displacement along the time-axis of the velocity curves determined from lines of different elements. This lag is related to the equivalent widths of the lines: the hydrogen lines are strongest, the helium lines are intermediate, and the lines of *Si* III, *O* II, etc., are weak. Hence, this effect is almost certainly one of level in the stellar atmosphere: the hydrogen lines are effectively produced above those of helium, and the latter originate at a higher level than the lines of *Si* III, *O* II, etc.

It is probable, but not certain, that the splitting of the absorption lines will fully account for the variation in line profiles, first discovered by Henroteau in β Canis Majoris, and since found to be present in five other members of the group. The broad lines

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TABLE I

Stars of the β Canis Majoris Group

Star	P_1	P_2	$2K_1$ (km/sec)	$2K_2$ (km/sec)	Δm_1	Δm_2	Spectral Type	Color	M_v	Line Profile	Rotational Velocity
β CMa	$6^h\ 0^m$	$6^h\ 2^m$	12	6	$0^m.03$	—	B1 II–III	—.280	—4.7	Changes	Large
σ Sco	5 44 or 6 7	5 55	15	110	—	0.08	B1 III		—4.3	Changes	Large
ξ^1 CMa	5 2	—	36	—	0.01 or 0.045	—	B1 IV	—.280	—4.2	Constant	Small
BW Vul = HD 199140	—	4 49	—	150	—	0.19–0.26	B2 III	—.270	—4.1	Changes	Average
12 DD Lac	4 44	4 38	15	36	0.042	0.074	B2 III	—.265	—4.1	Changes	Average
β Cep	4 34	—	18–46	—	0.02–0.05	—	B2 III	—.275	—4.1	Constant	Small
ν Eri	4 16	4 10	22	49	0.067	0.114	B2 III	—.255	—4.1	Changes	Average
16 EN Lac	4 6	4 4	9	30	0.035	0.055	B2 IV	—.260	—3.3	Changes	Small
δ Cet	3 52	—	13	—	0.025	—	B2 IV	—.245	—3.3	Constant	Small
γ Peg	3 38	—	7	—	0.015	—	B2 IV	—.240	—3.0	Constant	Small

The line profiles vary with period P_2. Small, average, and large rotational velocities represent projected equatorial velocities of the order of 15, 30, and 60 km/sec, respectively.

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result from the blending of incompletely resolved components. Hence, the broad lines cannot be used to determine the rotational velocities of these stars. Instead, we must use the sharp lines observed on the ascending branches of the velocity curves. The resulting values have been estimated in the last column of Table I. None is very large; whether the β Canis Majoris stars favor small rotations cannot be definitely decided. The radial velocities might not be measurable with sufficient accuracy when the lines are greatly widened by rotation. But the absence among rapidly rotating stars (—200 km/sec for $v_{rot} \sin i$) of variables with periods between three and one-half and six hours may be significant.

There is an indication in the table that interfering periods and multiple lines are associated with somewhat faster rotations than simple harmonic oscillations. Of special interest is β Canis Majoris. It is the only star in our list in which the change of line profile is associated with the oscillation of smaller velocity amplitude. Hence, the epoch of broadest lines seems to travel along the observed cycle obtained from the superposition of two sine curves. Van Hoof has investigated the "*H* minus other lines" time lag at two epochs in the beat cycle of this star: when $2K = 2K_1 + 2K_2$ and when $2K = 2K_1 - 2K_2$. The results suggest that the lag is the same. Unfortunately, the lines of this star are always too broad for the splitting to be observed.

It is tempting to believe that the two branches of the discontinuous velocity curves represent the two interfering oscillations in σ Scorpii, 12 Lacertae, etc. But BW Vulpeculae has only one period. Its velocity range has gradually increased, according to Petrie, but if there is a beat, the two interfering periods must be the same within a second, or less! Those of β Canis Majoris differ by two minutes. Until we can prove that BW Vulpeculae does have a beat phenomenon, it is necessary to assume that a single oscillation gives rise to the discontinuous velocity curve; and there is no reason why this should not be true also of two oscillations when both are present. Except in β Canis Majoris the one of larger $2K$ is the only one that shows the change in line profile, but it is quite possible that instrumental limitations prevent us from observing it in the oscillation of smaller amplitude.

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Since we cannot now advance a self-consistent theory of all of the phenomena shown by the β Canis Majoris stars, it may be useful to construct as simple a working hypothesis as possible in order to stimulate further research. Let us consider first BW Vulpeculae with its single period of $4^h\ 49^m$. We shall suppose that this is the true period of radial pulsation of the star appropriate to its mean density. We shall also assume that we do not directly observe the motion of the photosphere, but only that of a superficial layer expelled by the photosphere once every $4^h\ 49^m$. This hypothesis was first suggested by me some months ago, but I shall here quote from a recent discussion by G. J. Odgers:

> We suppose that what actually happens is that an atmosphere is expelled—over a short interval of 15 or 20 minutes or perhaps in spasms—and is then subject to a uniform deceleration until—after reaching its maximum extent—it falls back into the star. The passage of the ejected atmosphere back through the relatively stationary photosphere is marked by the gradual weakening and disappearance of the redward spectral lines, and the gradual strengthening of the lines at the stationary position, in such a way that the total equivalent width remains nearly constant. For an interval of about twenty-five minutes—the observations show that this interval varies somewhat because the faster the material was shot out the longer it takes to return and the shorter the stillstand—the surface of the star is visible and then an atmosphere is ejected, its outward passage through the stationary atmosphere being shown by the appearance of spectral lines to the violet, weak at first and then strengthening while the stationary lines weaken and disappear.

Odgers has also attempted to explain the origin of the beat phenomenon in other stars:

> Presumably the period between ejections of the stellar atmosphere is a fundamental period associated with the constitution of the star. Once the material is ejected the time of its arrival back at the surface is, so to speak, predetermined by the value of effective gravity of the star. It happens that this time is nearly equal to the period. In BW Vulpeculae it is less, and there is a stillstand. If the "flight-time" were greater there would be a beat, since that ejected atmosphere would travel furthest which did not collide with a returning

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atmosphere. Such an occurrence takes place precisely at intervals corresponding to the beat-period appropriate to the superposition of the "flight-time" and the fundamental period.

This hypothesis does away with the interference of two nearly identical periods *so far as the body of the star is concerned.* It does not attempt to explain the existence of the beat phenomenon in the light-curve. Nor does it take into account the frequent occurrence of similar—and even more complicated—beat phenomena in the RR Lyrae stars.

The hypothesis fails to explain why several stars have symmetrical velocity curves: in β Cephei, ξ^1 Canis Majoris, δ Ceti, and γ Pegasi there is no noticeable difference between the ascending and descending branches of the velocity curve. Are these stars physically so different from BW Vulpeculae? They have neither a "stillstand" nor a beat phenomenon.

Neither does the hypothesis make allowance for the fact that the stars rotate and have different projected velocities of $v_{\text{rot}} \sin i$. It therefore loses those aspects that made Ledoux's hypothesis of nonradial oscillations especially attractive.[4] Finally, attention should be given to the fact that the spectral types and luminosity criteria are almost identical for the two components of the lines in BW Vulpeculae. The ejected layer shows no *marked* increase in ionization or decrease of temperature. On the other hand, the occurrence of hydrogen emission in the ejected shell is consistent with the hypothesis.

Huang has recently drawn attention to the fact that the sum of the equivalent widths of the two lines during the double stage is the same as the equivalent width during the single stage. This suggests that the components came from different regions on the surface of the stars, rather than from layers, one above the other, as Odgers and I have postulated. Whether the observations are good enough to exclude our hypothesis remains to be seen.

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[1] *Pub. A.S.P.*, **46**, 202, 1934.

[2] *Pub. A.S.P.*, **60**, 285, 1948.

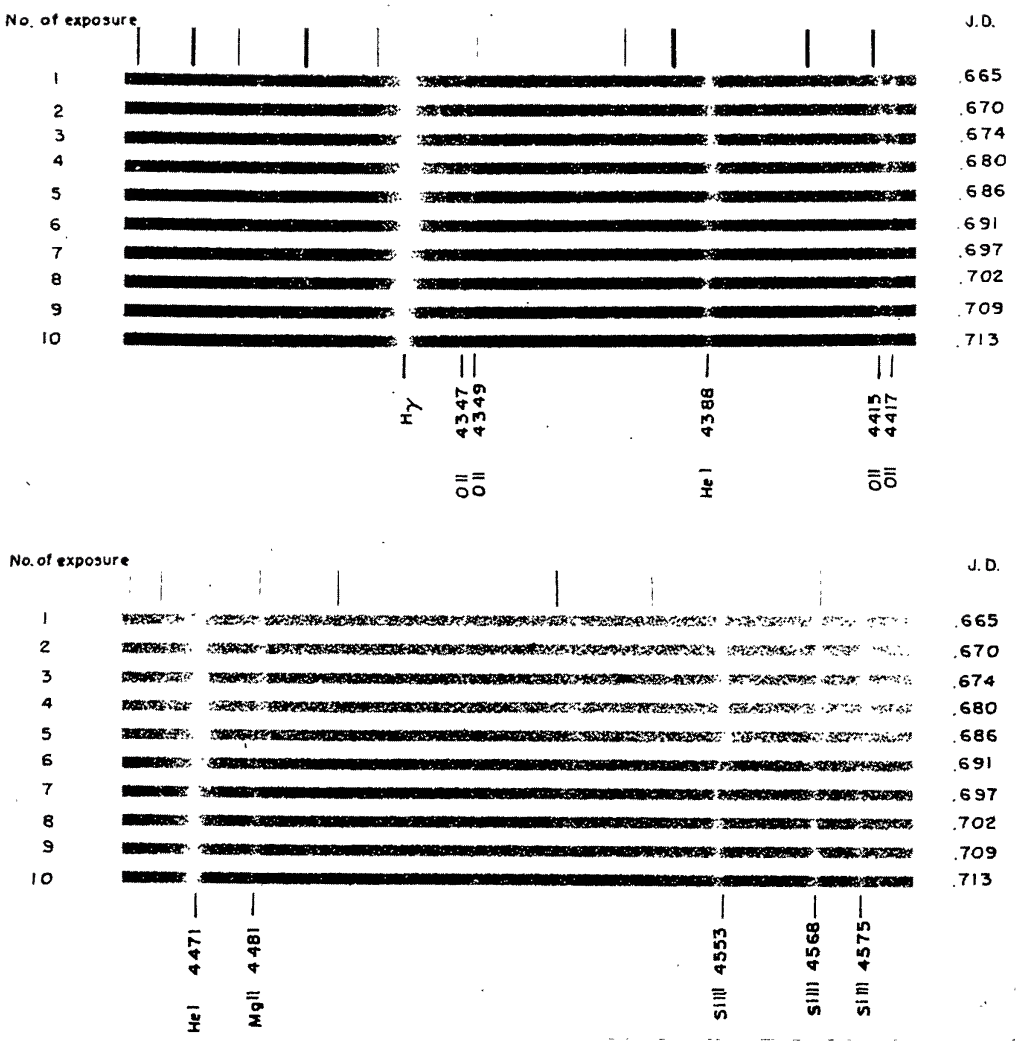
[3] The work in Berkeley has been partly supported by grants from the Research Corporation and the Office of Naval Research.

[4] *Ap. J.*, **114**, 373, 1951; see also O. Struve, *Ann. d'Astrophysique*, **15**, 157, 1952.

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PLATE 1

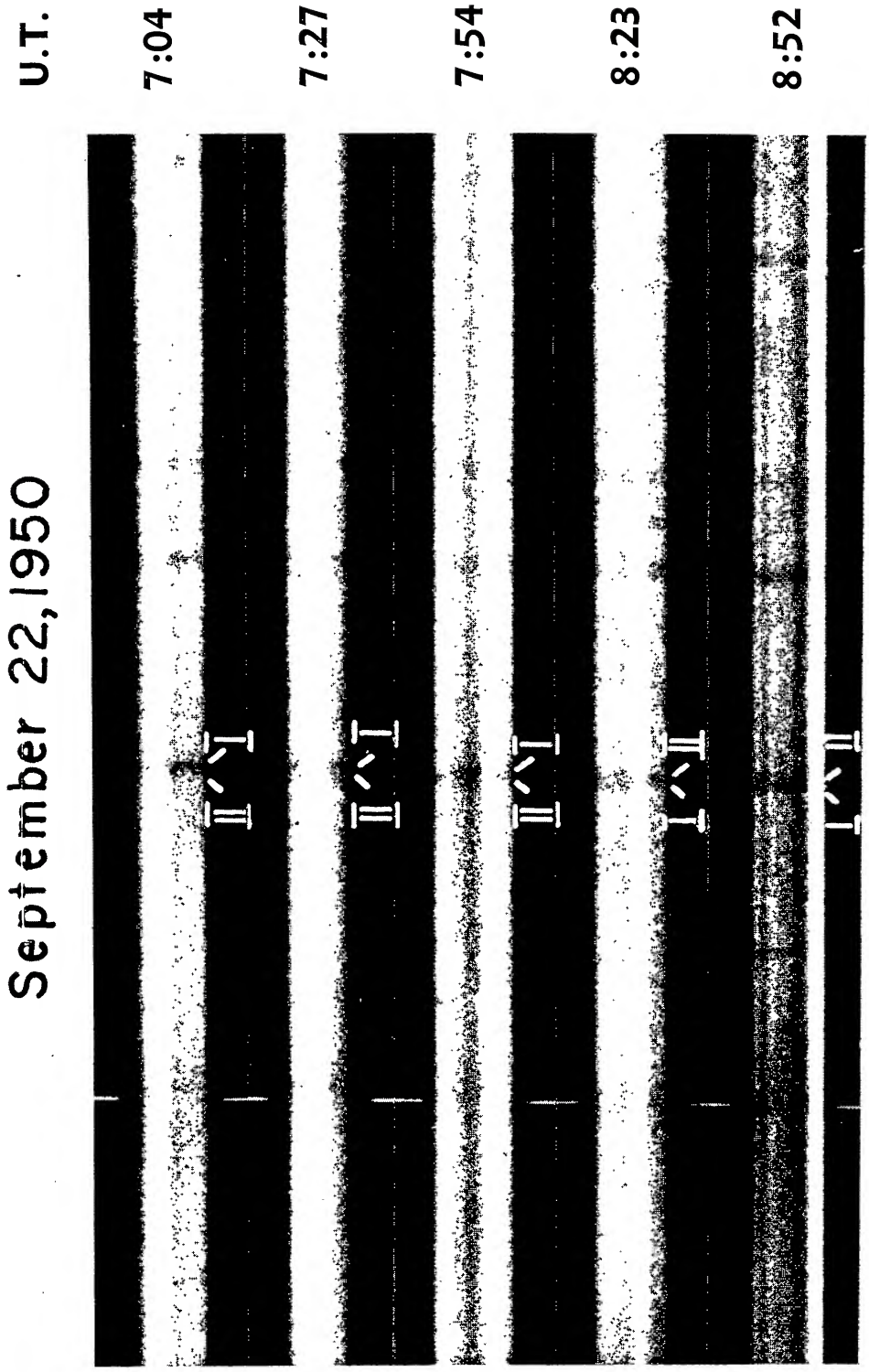


SPECTRA OF BW VULPECULAE BY DEUTSCH SHOWING DOUBLE LINES

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PLATE II



SPECTRA OF 12 LACERTAE SHOWING DOUBLE LINES OF *Si* III

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