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## Boulder Laboratories

# VARIATIONS OF GAMMA CASSIOPEIAE

BY S. R. POTTASCH

U. S. DEPARTMENT OF COMMERCE
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## *Technical Note*

21

August 1959

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# VARIATIONS OF GAMMA CASSIOPEIAE

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## ABSTRACT

The variations of Gamma Cassiopeiae between 1890 and 1950 are summarized and discussed. The variations of visual magnitude, color temperature, radius and electron density of the shell, and the spectral variations are depicted.

# I. INTRODUCTION

A. Gamma Cassiopeiae belongs to a class of stars commonly referred to as B emission stars. It is an irregular variable, whose visual magnitude varies not more than 1 magnitude on either side of its mean +2.25. Its 1900 position is: R.A.$0^h50^m.7$, Dec. +60°11'. The Henry Draper Catalog (HD 5394) gives it a visual magnitude of 2.25, a photographic magnitude of 2.01 and a spectral class of B0p.

Gamma Cassiopeiae has been assigned by the Yale catalog a trigonometric parallax of +0".034±11 which corresponds to a distance of 31±15 parsecs. This leads to an absolute magnitude of -0.5 which is sub-luminous for a B0 star. Caution is always advised in the use of trigonometric parallaxes under +0".050, so that no definite conclusion may be drawn. Application of the criterion suggested by Petrie to determine the absolute magnitude from the equivalent width of Hγ has been applied, and an absolute magnitude of -5.0 derived, corresponding to a parallax of +0".0031 and a distance of 320 parsecs. The star has a proper motion: $\mu\alpha$ = +0".026, $\mu\delta$ = -0".002, and has an 11th magnitude companion 2" from it which shows common proper motion.

B. The observations, which it is the purpose of this paper to compile and discuss, are of three types:

1. Spectra and spectral data
2. Visual and photographic magnitudes
3. Color temperatures, gradients, and colorphotometry.

The observations have been taken by many people with different instruments. In the present compilation when the same data were available for smaller time intervals than 3 months, only 3 month averages were used. There are two reasons for this:

1. Observations are not consistently available for such small time intervals.

2. The unaveraged data show marked irregularities sometimes over a period of hours or days. Most of this is due to instrumental and measuring inaccuracies, but some seems to be real. However, considering these variations to be real, absolutely no pattern was discernible.

It was thereforethought advisable to first try to understand the larger scale time variations and to wait for the data to become available to study the small time scale variations.

## II. THE VARIABILITY OF $\gamma$ CASSIOPEIAE

### A. 1830 - 1928

1. Edwards (1944) studied the records of the magnitude of $\gamma$ Cas. which were available at various periods from 1830 - 1942. He supplemented this with radial velocity from the period 1911 - 1914 and some spectroscopic data from the period 1924 - 1932. He came to the conclusion that "a periodicity is suggested for these changes, consisting of two maxima, separated by 4.30 years, in a main period of 10.67 years".

His work can be criticized on the following grounds: Considering only the period before 1928:

a) He does not have a consistent series of measures of any one quantity covering even two of his periods.

b) The variations that he based much of his argument on are in most cases at or below the probable errors which should be assigned to the quantities in question.

c) Many of his supposed maxima are found, as for example in his discussion of the radial velocity measures over a three year period, by extrapolating a curve, thru which a straight line might easily satisfy the data to the accuracy inherent in the measurements, to maxima on either side of the data. The maxima are then separated by almost seven years.

On the basis of the present data, it seems that no large scale periodic variability was present during the period before 1928. The question of small scale variability, at the edge of instrumental accuracy, is an open one.

2. Lockyer (1933 a,b, 1935 a,b, 1936) made a study of the variability of $\gamma$ Cassiopeiae from plates taken at Sidmouth from the period 1892 - 1895 and again from 1921 to 1934. He states that as far as he can detect, the magnitude of the star remained constant before 1932. He looked for variability in the structure of the emission lines of hydrogen. The lines are seen as wide emission lines with a central absorption. This absorption may shift its position within the emission line causing the ratio of the violet part of the emission line to the red part of the emission, to vary. This will be referred to as V/R variability. Lockyer, from his measures of this quantity for H$\gamma$ and H$\delta$ said he was able to detect variability between 1921 and 1928, within a period of about 4 years. His conclusion

for this period is open to question on the following grounds:

a) Only 13 spectra were available in this 7 year period.

b) He measured Hγ both by eye and with a calibrated wedge. The difference between these measures for any single spectrum is about equal to the amount of the variability. Clearly, since the variability that he detects is so close to the observational error, the question cannot be said to have been settled. A period certainly cannot be said to have been determined.

3. Cleminshaw (1936) using 160 spectrograms obtained during an interval of 21 years (1914 - 1935) states that "observations made from 1914 through 1928, like those made by R. H. Curtiss (1916) from 1911 to 1914, do not show any undoubted variation in radial velocity or in the emission ratio V/R.

The conclusion is that the velocity and emission ratio remained constant from 1911 through 1928, except for possible short-period variations of small amplitude.

B. Spectra 1895 - 1924.

Considering that the most minor changes only occurred in γ Cas. in the period before 1928, it is felt warranted to compile a composite spectrum for the star in this period. This composite spectrum is based chiefly on the work of R. H. Curtiss, and secondarily on the work of Sidgreaves (1899), Miss Maury (1897), Baxandall (1914) and Miss Heger (1922). The composite spectrum is shown in Table I.

There are individual differences between the spectra which might indicate some degree of variability. But the measures are not complete enough for a definite statement to be made. For example, Sidgreaves sees a good deal more NII than any other observer, while Curtiss sees SII. Miss Heger, looking in the red, see a great deal of FeII, and FeII was probably stronger when she observed it than for the other observers. The identifications given in Table 1 are my own.

The radial velocity as derived from the absorption lines remains constant at about -6.8±4.0 Km/sec. during this interval.

1929 - 1935.

After 1928, systematic changes begin to be observed in the spectrum. Cleminshaw (1936) and Lockyer (1935a) observed an increase and then a drop in the emission ratio V/R (Figure 8). The spectrum

was observed by Struve and Swings (1932) in about 1931 and seems to have changed a little in the following way: the singly ionized metals appear to be stronger in emission, possibly [FeII ] appears, CrII appears for the first time, and the hydrogen lines appear stronger in emission. The HeI lines are still the most prominent part of the absorption spectrum and HeII still appears to be present, as does OII, NII, SiIII, SiIV, in absorption.

The main features of the data derived from spectral observation are plotted. Figure 1 shows the radial velocity, Figure 3 the width of the hydrogen lines in kilometers/sec., while the temperature variations, of which more will be said later, are shown in Figure 6.

In 1932 there was a marked change of the V/R ratio. The violet emission component became much stronger than the red, and the radial velocities, which had been small and negative, were observed by Cleminshaw (8) to become small and positive. The FeII lines underwent similar changes to the hydrogen lines. The temperature of the star began to decrease while the width of the hydrogen lines showed an increase.

In 1934 a new cycle of changes began. Heard (1938) and Cleminshaw (1936) observed the separation of the two emission components of the H and FeII lines to decrease, the lines becoming single in May 1934. Cleminshaw assumed the strong violet and weak red components approached until unresolved, blended, became equal in intensity, reversed inequality, and then separated again. This is in agreement with typical Be variables in which the separation of the two emission components is least when they are equal in intensity. The width of the H decreased while the temperature shows an increase.

By November 1934 the central absorption lines of H were distinct again, now with the red emission components stronger than the violet. The red component reached maximum strength in March 1935, after which McLaughlin (1936) observed the violet components to increase in strength until equality was reached in May 1936.

Heard (1938) observed that several plates taken in 1934 showed HeI 4471 in emission as well as absorption. This had not been observed before, the HeI always had appeared as simple, broad, hazy absorption lines. He also noted the presence of HeI 3889, indicated by the enhancement of H8.

The Balmer series could be traced in emission to H 20 at this time. V/R variations for FeII and HeI were also measured and found similar but smaller than those for H.

Beginning in August 1935, a very sharp absorption due to HeI 3889 began to appear. It was followed by the appearance of other sharp HeI absorption lines. The strongest: λ3965, λ4026, λ4471 were as sharp, although not as strong as λ3889.

Simultaneously with the appearance of these sharp HeI lines, an increase in the strength of the H central absorption was observed. Measures of the blend H8 and HeI showed that after September 1935 this strong line was due almost entirely to HeI. FeII generally behaves similarly to H and HeI.

1936 - 1939.

A detailed description of this period is given by Baldwin (1938, 1939 a, b) from a series of 70 spectrograms obtained between March 1935 and October 1938.

Table II is a summary of the spectrum of γ Cassiopeiae, primarily for 1937 although the spectrum was very similar for the few years preceding it. The wavelengths were taken from Baldwin (1938), Belorizky (1952), Cherrington (1938), all of whom cover the period of the middle of 1937, with reference to the work of Heard (1935) and Struve and Swings (1932). The intensities up to Hβ are adopted from Baldwin, while from Hβ to Hα, W,M,S,SS,SSS are used to indicate an increasing intensity. The identifications are, as in Table I, the responsibility of the present writer. The spectrum is entirely one of emission. An underlying broad absorption of about 600 Km/sec. width is seen continuously over the entire period but no identification or wavelengths are available. Presumably this broad absorption never changes and is the same as that seen clearly in the 1950's (to be described).

After June 1936, a sudden decrease of strength of the sharp absorption lines of H and HeI was noted. At the end of this decrease, all the HeI lines, except 3889, appeared as widely separated emission pairs with no sharp absorptions between, while HeI 3889 was present in absorption until the end of February 1937. After this fading of the absorption lines, or possibly beginning coincidently with this fading, there occurred a steady increase of the emission intensity in all the lines, and the two emission components were observed to approach each other. This narrowing recalls the occurrence of this phenomenon in 1934. The emission edges of the broad shallow absorption lines of HeI began to sharpen and approach each other, remaining, however, equal in intensity during the entire period (through 1938) except $D_3$(5876). The violet components of the H lines steadily strengthened as the two components approached each other. The FeII lines, which were formerly observed to be merely diffuse patches of emission, so that only a few lines were measurable, sharpened and strengthened, as did the SiII and MgII emission components, until all the emission pairs blended to single lines in 1937.

The narrowing of the emission lines coincides with the large rise in visual magnitude. The single line stage coincides exactly with maximum light. Minimum temperature also occurs at this time.

By the end of November 1937, the lines had widened and were just resolvable as double emission lines, with the red component equal to, or slightly stronger than the violet. By the end of December, the H lines were clearly separated, with the violet component strong but rapidly decreasing in strength. The HeI and FeII lines had widened and weakened but did not clearly separate until later.

Then a new and unexpected feature was observed in the lines of all of the elements studied. In April 1938, the lines suddenly became fuzzy and almost unmeasurable, and examination disclosed that a second pair of emission lines, too close to be fully resolved, had appeared in the position previously occupied by the central absorption line. These faded by August 1938, and the old pair strengthened again.

During 1938, the spectrum was again characterized by absorption lines, which were not as strong, however, as those in 1936. H and HeI appeared more strongly than the other elements. This stage seems to be followed by another emission line phase, but it is neither long nor well marked.

Then, in the autumn of 1939, the sharp absorption lines reappeared in greater strength and numbers than ever before.

1940 - 1954.

Table III shows the observed spectrum at the beginning of 1940, as before, in the region between H9 and H$\alpha$. Spectra are available down to 3100A during this period, mainly due to Baldwin (1941) and Struve and Elvey (1940). H and HeI are the strongest features of the shell absorption spectrum, with lines of FeIII appearing in large numbers, particularly in the ultraviolet. It cannot be said that any other element or stage of ionization is definitely seen at this point (December - January, 1939 - 1940). There are a large number of unidentified lines which Baldwin has suggested might be due to TiIII, NiIII, and CrIII and perhaps other doubly ionized metals; their spectra, however, are practically unknown. It should be mentioned that all of the FeIII lines observed arise from a metastable level. No others are conspicuously observed.

Changes in the spectrum occur rapidly. In March 1940, Swings and Struve, observing in the visible region found that the sharp absorptions were weaker, and the underlying broad absorption lines which had been veiled, became much more conspicuous. They also note the presence of SiIII, half in absorption, half in emission.

The last part of 1940 and 1941 was characterized by the further conspicuousness of the broad absorption although many sharper lines are still seen. FeIII is still present and familiar lines of OII, NII, CII, CIII, SiIII and SiIV are beginning to be observed. MgII is present in absorption. Detailed descriptions of the spectrum at this period may be found from Peachey (1942, 1944), Hase (1940) and Tcheng Mao-Lin (1941).

Detailed observations on high dispersion equipment are not available during the next seven years. Morgan observed the spectrum toward the end of 1941 and classified it as BOIV peculiar. The blend at 4650 (CIII, OII) was prominent and little or no emission was seen. The star was again observed in October 1944 by Belorizky (1945) who found the broad absorption lines of H and HeI, but found no emission at all. The emission reappeared again in September 1946 (Belorizky and Fehrenbach, 1947) and is seen continuously toward the red end of the spectrum from then until the present. Table IV shows the observations of 1946.

The variations in the spectrum during the whole period seem to be of a minor variety. The spectrum was again observed in 1949 by the Burbidge's and Wang (1952). At this period Hα, HeI 5876 and Hβ were seen in emission, and the remainder of the lines were broad shallow absorptions, which included H, HeI, OII, SiIII, SiIV, NII, CII and SIII, a spectrum very reminiscent of the broad shallow absorption lines observed by Curtiss in 1914. The radial velocity was determined for this period and a continuous record for the period of one month was obtained for the equivalent widths of several H, HeI and OII lines. The variations were periodic and amounted to ±2 Km/sec. but their reality may be doubted.

The period between 1947 and 1954 is summarized in Table V; most of the information is due to Kopilov and his co-workers (1954, a,b,c). They attempt a characterization of the profile of the lines, although with their equipment this is a difficult task. The quantities given in Table V are: Wλ is the equivalent width, v is the total width of the absorption line in Km/sec, r is the intensity at the center of the line divided by the intensity of the continuum at that point, and Δλ is the half width of the line in angstrom units.

The H lines appear to be wider than the others, probably due to Stark broadening. The average width of the HeI lines is 663 Km/sec, while that of the other lines is 661 Km/sec. The velocity of rotation of some layer at which most of the elements can be said to originate (an effective photosphere) is 331 Km/sec.

Kopilov also indicates that he feels that superimposed on the broad shallow absorption line is a weak, but much sharper absorption, at least in the case of the hydrogen lines. He finds this absorption to have a whole width of 170 Km/sec. Thus it would arise in a shell or ring surrounding the star at distance of four radii from the star.

During 1950 the star brightened by about 0.5 magnitude and then fell again. No spectra were taken during this occurrence, however.

C. References of further spectral work done on Gamma Cassiopeiae: Koelbloed and Walraven (1940) took several spectrograms of the star in 1939 while the emission was present but declining and measured the equivalent widths of the emission and absorptions lines observed. Roach and Blitzer (1940) measured the equivalent widths of the HeI lines, probably late in 1939, but no date is given. Merrill and Wilson (1941) have also measured equivalent widths of several lines at and around November 1940. A study of the profiles of the Hδ lines is given from about 1930 to May 1940 by Baldwin (1941) and from Jan. 1940 to Jan. 1941 by Swings and Struve (1941) who also give the profiles for several other lines (OII, SiIV) during the same period.

Radial velocities during this period are given by Smith and Struve (1950).

## III. DERIVATIONS FROM SPECTRAL MEASUREMENTS

A. The Rotation of the Star.

Curtiss has shown that the width of the emission lines varies directly as the wavelength. Kopilov has shown that this is true of the absorption lines too, and that they may be characterized as "broad, shallow, dish-shaped." Struve (1930) has shown, from data which included a study of spectroscopic binaries, that these characteristics arise from the rotation of the star. Assuming the conservation of angular momentum in the atmosphere of the star, $r\,v$ = constant.

A parameter Ro is used to indicate the effective photospheric radius for all the lines between '52 and '54. The great bulk of the star lies within this radius at any period and it appears to be a more or less non-varying radius for the production of the broad absorption lines.

Figure 4 is a plot of the effective radius for the production of emission lines at any given date. Before 1930 it remained constant at about 2 Ro. It varied greatly after this date, a maximum of about 3 Ro was reached at the end of 1934 and an effective photospheric radius of about 10 Ro was reached in the summer of 1937. After 1940 the emission lines weaken and disappear.

B. The Balmer Decrement.

Measurements are available of the equivalent width of the Balmer lines in emission, by Karpov (1932) and for Nov. 1937 by Wellman (1951). These are shown in Table VI. Column A gives the equivalent width in A times the height of the continuum. Column B gives a multiplying factor to reduce these values to a uniform intensity scale. A black body distribution was assumed at T = 15,000 K. An error is introduced with this assumption because the continuum cannot be represented by a black body, but the factor will not be relatively very sensitive. Column C then gives the relative intensities in arbitrary units.

TABLE VI

| | A | | B | C | |
|---|---|---|---|---|---|
| LINE | EQUIVALENT WIDTH | | 15,000°K MULT.FACT. | EMISSION IN BALMER LINE ARB. UNITS | |
| | 1932 | 1937 | | 1932 | 1937 |
| Hα | 47.41 | 114.-- | 0.41 | 26.7 | 26.7 |
| Hβ | 7.31 | 17.5 | 1. | 10.0 | 10.0 |
| Hγ | 2.70 | 6.85 | 1.36 | 5.02 | 5.2 |
| Hδ | 1.48 | 3.36 | 1.58 | 3.24 | 2.9 |
| Hε | 0.76 | 2.06 | 1.71 | 1.78 | 1.9 |

C. The Radial Velocity and the V/R Emission Ratio.

Figure 1 is a plot of the radial velocity as determined by the absorption lines of Hδ and Hγ. Each point shown is the average of many taken over a three month interval and the error is probably not greater than ±3 Km/sec. for the average. All peaks are of undoubted reality. The dotted line is the average of all readings before 1928, with great weight being given to the work of Curtiss (1914) and is presumed to be the radial velocity of the star (-7.0 Km/sec.).

The V/R ratio has been discussed before. It can be very accurately determined. It does not extend past 1940 because emission generally does not exist past this date. The general presumption has been that in a case like this, the V/R ratio is caused by a fixed emission surface, surrounded by an absorbing shell; the motion of this absorbing shell back and forth produces an absorption line which moves across the emission line producing the V/R ratio. From the data, this could be true for the 1934 V/R peak. After that, the absorption velocity by itself (on top of a fixed emission) could not have produced the observed V/R ratio. Qualitatively it can be stated that during 1935 the emission photosphere contracted with the absorption shell fixed, then, in 1936 the emission photosphere expanded as did the absorption shell. In 1938 the emission continued to expand, with the absorption shell slowing but not halting until 1940, after which time some of it is drawn back to the star but the greater part, in expanding, lost direct spectral connection with the star.

This discussion is rendered difficult by the fact that the observed radii (Figure 4) are only indirectly formed by the observed expansion or contraction. The point in the atmosphere at which the optical depth = 1 may have far greater velocities of both expansion and contraction than the actual velocity of the material in the atmosphere of the star.

D. The Number of Hydrogen Lines Observed and the Electron Density Derived from this.

Figure 5 is a plot of the electron density derived from the Inglis-Teller formula from the number of H lines observed. The last observable H line is indicated next to each point.

An order of magnitude estimate of the mass in the outer layers of $\gamma$ Cas. may be made from the electron density. Assuming the absolute magnitude is -5.0 for that part of the star associated with the spectrum showing the wide absorption lines, and assuming the spectrum is B0, corresponding to a temperature of 25,000°K, then $R_o$ is 15 solar radii. The total mass above the photosphere is then of the order of $10^{29}$ grams and the mass associated with the shell that caused the absorption spectrum of 1940 is $5 \times 10^{27}$ grams.

It is seen that the distinction that has been used for convenience in description, that between emission photosphere and absorption shell, is in reality meaningless. These parts of the star are probably close together in space as indicated by the density of the absorption shell after 1939. This was previously indicated by the closely associated movement of the two levels. It is even probable that the same atom may take part in both phenomena at different times and still remain reasonably fixed in space.

## IV. THE VISUAL MAGNITUDE

The problem of determining the magnitudes of this star with the existing data is a difficult one and if accuracy of 0.1 magnitudes is desired, an insoluble one. Observations of this star prolonged over a period of a year or two by professional astronomers are rare.

The most valuable contribution to this end are the photoelectric magnitudes of Huffer (1939) from Nov. 1936 to Nov. 1938. Edwards (1942) has determined both the visual and photographic magnitudes for the period July 1940 to March 1942. Other observations considered include those of Rigollet (1936) who gives measures on widely spaced dates from 1928 to 1936, de Vaucouleurs (1947) and some further measures by Rigollet (1943 a,b).

Among the amateurs, the period between 1937 and the present has been covered. P. Moore has observed the star over that period and the AAVSO has on the average 10 observations per month of this star. These observations are consistent with Huffers work and that of Rigollet and de Vaucouleurs but do not agree well with Edwards work.

Figure 2, a plot of the visual magnitude from 1928 to the present, is probably better determined before 1940. All irregularities of the order of magnitude of the probable error have been smoothed. All bumps are undoubtedly real.

## V. THE COLOR TEMPERATURES

The majority of the measures of color temperature were taken as relative gradients in the system of Greenwich (Greaves and Martin 1938, Vanderkerkhove 1937, 1939, 1952, Hunter and Martin 1939, Edwards 1943, Hiltner 1941, Barber 1946, 1950). In most cases the two wavelengths used were $\lambda$4250 and $\lambda$5800, although the latter wavelength varied from $\lambda$5100 to $\lambda$6700, and even $\lambda$7100. The gradients varied with wavelength used, and an attempt has been made to reduce the temperatures to a common system, which is described by Greaves and Martin (1938). The measures are shown in Figure 6a. Included are determinations by Hiltner (1941) who used an absolute gradient and 11 wavelengths between $\lambda$4050 and $\lambda$6360. His results indicate a large scale temperature variation in a period of eight weeks at the end of 1940. It is not substantiated by Barber (1946), observing at the same time, and is smoothed out in the three month averages plotted.

Figure 6b is a plot of the absolute gradients of Barbier and Chalonge, as reported by Barbier (1948). Not as many measures are available as in Figure 6a. $\varphi_1$ is the temperature measured at $\lambda$4250, $\varphi_2$ is measured at $\lambda$3500. Measures of the Balmer discontinuity D, (Figure 7) are also available and serve to point up the strength of the Balmer emission.

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TABLE I

GAMMA CASSIOPEIAE — COMPOSITE SPECTRUM 1890 - 1928

| λ | ABS. | EM. | INTENSITY | IDENTIFICATION |
|---|---|---|---|---|
| 3889 | x | x | 6 | H8 |
| 3912.2 | x | | | OII(17) |
| 3920 | x | | 5 | CII(4) and OII(17) |
| 3927.4 | x | | 4n | HeI(58) |
| 3930.4 | x | | 8 | SII(29) 3931.9 |
| 3933.8 | x | | 3.6 | CaII(1) |
| 3935.7 | x | | 5 | HeI(57) |
| 3970.2 | x | x | 14 | Hε |
| 3983 | x | | 2 | OII(6) |
| 3995 | x | | 4 | NII(12) |
| 4009.5 | x | | 6 | HeI(55) |
| 4010.7 | x | | 8 | CII(27) |
| 4011.4 | x | | 5 | (?)AII(53) |
| 4026.5 | x | | 12n | HeI(18) |
| 4037 | x | | 2 | (?)AII(2) + NII(39) |
| 4043 | x | | 2 | NII(39) |
| 4065 | | x | 4 | NiII (4067.1)? |
| 4067.2 | x | | 4 | CIII(16) |
| 4069.5 | x | | 4 | CIII(16) |
| 4071.5 | x | | 5 | OII(49) + OII(10) |
| 4073.5 | x | | 5 | CII(36) + OII(10) |
| 4089.4 | x | | 7n | SiIV |
| 4101.9 | x | x | 20 | Hδ |
| 4116.4 | x | | | SiIV |
| 4118.9 | x | | 8 | OII(20) 4119.2 |
| 4120.8 | x | | | HeI(16) |
| 4131 | | x | 6 | SiII 4130.9 (3) |
| 4141.2 | x | | 3 | SII(44) 4142.3 (?) |
| 4144 | x | | 8n | HeI(53) |
| 4145.9 | x | | 5 | SII(44) 4145.1 ? |
| 4155 | x | | 2 | OII(10) |
| 4169.6 | x | | 9n | HeI(52) |
| 4177.6 | x | x | 3 | FeII(28) |
| 4185 | x | | 4 | OII(36) + CIII ? |
| 4200.2 | x | | 4 | HeII(3) |
| 4207 | | x | 5 | MnII(2) ? |
| 4214.6 | | x | 3 | SrII(1) 4215.5 |
| 4233.6 | x | x | 5 | FeII(27) |
| 4239 | x | | 2 | NII(48) |
| 4253.8 | x | | 2 | SIII |
| 4260.1 | | x | 4 | FeII(28) + MnII(2) ? |
| 4267.4 | x | | 7n | CII(6) |
| 4271.8 | | x | 5 | FeII(27) |
| 4282 | x | | 4 | SII(49) ? |
| 4285 | x | | 4 | SIII(4) |
| 4295.3 | x | | 8 | OII(54) + SII(49) ? |
| 4302 | | x | 4 | FeII(27) |
| 4307 | x | | 4 | OII(53) ? |
| 4317.8 | x | | 10n | OII(2) |
| 4326 | x | | 6 | OII(2) + CIII(7) |
| 4340.6 | x | x | 24 | Hγ |
| 4353.3 | | x | 4 | FeII(27) |
| 4367.2 | x | | 7n | OII(2) |
| 4384.2 | x | x | 5 | FeII(27) |
| 4388.1 | x | | 6 | HeI(51) |
| 4390.9 | x | | 4 | SII(43) |
| 4395 | | x | 3 | |
| 4400.5 | x | | 3 | AII(1) |
| 4403.1 | x | | 4 | |
| 4416.8 | x | | | OII(5) |
| 4418.8 | x | x | 4 | FeII(27) |
| 4431 | x | | | SII(43) ? |
| 4437 | x | | | HeI(50) |
| 4451 | x | | 2 | OII(5) |
| 4462.2 | | x | 3 | FeIII(106) ? |
| 4469.4 | x | | 7 | |
| 4471.8 | x | | 5 | HeI(14) |
| 4481.3 | x | x | 3 | MgII(4) |
| 4484.6 | x | | 3 | SII(43) |
| 4491.5 | x | x | 4 | FeII(37) |
| 4521 | | x | 3 | FeII(37), (38) |
| 4557.5 | | x | 4 | FeII(37) CrII |
| 4572 | x | | 5 | SiIII(2) ? |
| 4584 | x | x | 6 | FeII(38) |
| 4596 | x | | 4 | OII(15) |
| 4612 | x | | 5 | NII(5) |

TABLE I (Cont.)

| λ | ABS. | EM. | INTENSITY | IDENTIFICATION |
|---|---|---|---|---|
| 4629 | | x | 6 | FeII(37) |
| 4640.8 | x | | 5 | OII(1) |
| 4649.6 | x | | 5 | OII(1) CIII(1) |
| 4651.0 | x | | 11 | CIII(1) |
| 4653.1 | x | | 4 | SiIV(7) ? |
| 4657.0 | | x | 7 | FeII(37) |
| 4662 | x | | 6 | OII(1) |
| 4668 | | x | 6 | FeII(37) |
| 4676 | x | | | OII(1) |
| 4685.8 | x | | 6 | HeII(1) |
| 4713.3 | x | | 5 | HeI(12) |
| 4861.5 | x | x | 24 | Hβ |
| 4925 | | x | 5 | FeII(42) |
| 5006 | x | | 6 | NII(19) |
| 5018 | x | x | 5 | FeII(42) |
| 5048 | x | | 7 | HeI(47) |
| 5105 | x | | 8 | NII(34) |
| 5161 | x | | 4 | OII(32) ? |
| 5169 | x | x | 6 | FeII(42) |
| 5174 | x | | 4 | OII(32)? |
| 5180 | x | | 5 | NII(66) ? |
| 5186 | | x | 3 | |
| 5214 | | x | 3 | |
| 5234 | | x | 4 | FeII(49) |
| 5256 | x | | 3 | CII(30) ? |
| 5278 | | x | 3 | FeII(49) |
| 5281 | x | | 5 | |
| 5286 | | x | 3 | FeII(41) |
| 5294.5 | x | | 6 | |
| 5316.6 | | x | 4 | FeII(49) |
| 5327 | | x | 2 | FeII(49) |
| 5353 | x | | 10 | NII(69) ? |
| 5376 | x | | 7 | |
| 5411 | x | | 4 | HeII(2) |
| 5426 | | x | 3 | FeII(49) |
| 5523 | x | | 5 | SII(11) |
| 5538 | | x | 4 | FeII(55) |
| 5576 | | x | 2 | FeIII(68) ? |
| 5760 | x | | 5 | NII(9) ? |
| 5862 | x | | 6 | |
| 5876 | | x | 5 | HeI(11) |
| 5882 | x | | 6 | |
| 5953 | | x | | FeII(182) ? |
| 6149 | | x | 4 | FeII(74) |
| 6236 | | x | | FeII(74) |
| 6247 | | x | | FeII(74) |
| 6273 | | x | | |
| 6278 | x | | 12 | SII(19) |
| 6307 | x | | 7 | SII(19) + HeII(7) |
| 6320 | | x | 4 | ScII |
| 6340 | x | | 9 | NII(46) |
| 6351 | | x | 4 | SiII |
| 6367 | x | | 6 | SII(19) |
| 6370 | | x | | FeII(40) |
| 6384 | | x | | FeII 6383.8 |
| 6418 | | x | | FeII(74) |
| 6431 | | x | | FeII(40) |
| 6456 | | x | | FeII(74) |
| 6492 | | x | | FeII 6493 |
| 6514 | | x | | FeII(40) |
| 6563 | x | x | 40 | Hα |

TABLE II

EMISSION SPECTRUM 1937

| Wavelength | Intensity | Identification |
|---|---|---|
| 3835.35 | 18 | H9 |
| 3849.46 | 0.7 | NiII (11) |
| 3853.70 | 1.5 | SiII (1) |
| 3856.00 | 6.5 | SiII (1) |
| 3862.60 | 5. | SiII (1) |
| 3888.76 | 25. | HeI and H8 |
| 3930.34 | 1. | |
| 3933.68 | 1.5 | CaII (1) |
| 3938.41 | 1. | FeII (3) |
| 3964.74 | 5. | HeI (5) |
| 3968.58 | 1. | CaII (1) |
| 3970.09 | 20. | Hε |
| 4009.34 | 1. | HeI (55) |
| 4026.26 | 8. | HeI (18) |
| 4067.09 | 2. | NiII (11) |
| 4101.68 | 25. | Hδ |
| 4120.82 | 2.5 | HeI (16) |
| 4122.79 | 1.5 | FeII (28) |
| 4128.22 | 3.5 | SiII (3) |
| 4130.88 | 3.5 | SiII (3) |
| 4143.79 | 3. | HeI (53) |
| 4173.42 | 5. | FeII (27) |
| 4178.88 | 6.5 | FeII (28) |
| 4233.16 | 9.5 | FeII (27) |
| 4246.0 | 2. | ScII (7) |
| 4258.15 | 1. | FeII (28) |
| 4273.25 | 1. | FeII (27) |
| 4281.2 | 2. | |
| 4296.5 | 3.5 | FeII (28) |
| 4303.18 | 5.5 | FeII (27) |
| 4314.18 | 0.7 | FeII (32) and ScII (14) ? |
| 4340.40 | 40. | Hγ |
| 4351.76 | 7. | FeII (27) ? |
| 4369.29 | 0.7 | FeII (28) |
| 4374.0 | 1. | ScII (14) ? |
| 4385.22 | 3.5 | FeII (27) |
| 4387.96 | 3. | HeI (51) |
| 4416.77 | 3.5 | FeII (27) |
| 4471.53 | 18. | HeI (14) |
| 4481.23 | 12. | MgII (4) |
| 4489.13 | 2.5 | FeII (37) |
| 4491.54 | 3. | FeII (37) |
| 4508.28 | 5. | FeII (38) |
| 4515.42 | 4.5 | FeII (37) |
| 4520.18 | 4. | FeII (37) |
| 4522.81 | 4. | FeII (38) |
| 4534.25 | 1. | FeII (37) |
| 4541.62 | 1.5 | FeII (38) |
| 4549.48 | 7. | FeII (38) |
| 4555.91 | 4.5 | FeII (37) |
| 4558.66 | 1.5 | CrII (44) |
| 4576.3 | 2. | FeII (38) |
| 4583.78 | 9.5 | FeII (38) |
| 4588.01 | 0.7 | CrII (44) |
| 4618.32 | 0.7 | CrII (44) |
| 4629.45 | 5. | FeII (37) |
| 4666.79 | 0.7 | FeII (37) |
| 4713.30 | 3.5 | HeI (12) |
| 4731.71 | 1.5 | FeII (43) |
| 4861.39 | 25. | Hβ |
| 4923.94 | 0.7 | FeII (42) |
| 5015 | S | HeI |
| 5018.5 | S | FeII (42) |
| 5040 | M | SiII |
| 5060 | S | SiII |
| 5168.9 | S | FeII (42) |
| 5197.8 | S | FeII (49) |
| 5234.8 | S | FeII (49) |
| 5275.8 | S | FeII (49) |
| 5284.2 | M | |
| 5316.4 | S | FeII (49) |
| 5326.2 | W | |
| 5362.5 | S | FeII (48) |
| 5534.8 | S | FeII (55) |
| 5875.6 | SS | HeI (11) |
| 5979 | M | |
| 6148.9 | M | FeII (74) |
| 6238.6 | W | FeII (74) |
| 6248.4 | M | FeII (74) |
| 6318.3 | S | ScII ? |
| 6347.3 | S | SiII (2) |
| 6371.0 | M | SiII (2) |
| 6384.2 | S | FeII |
| 6417.4 | M | FeII (74) |
| 6432.7 | W | FeII (40) |
| 6443.9 | M | FeII |
| 6455.9 | S | FeII (74) |
| 6492 | M | FeII |
| 6516.2 | W | FeII (40) |
| 6562.7 | SSS | Hα |

TABLE III

ABSORPTION LINE SPECTRUM
1939 - 1940

| Wavelength | Intensity | Identification | Wavelength | Intensity | Identification |
|---|---|---|---|---|---|
| 3835.41 | 18 | H9 | 4101.72 | 19 | Hδ |
| 3837.88 | 2 | HeI(61) | 4120.84 | 5 | HeI(16) |
| 3845.62 | 2 | | 4125.01 | 0 | |
| 3849.47 | 0 | NiII(11) | 4127.07 | 0 | |
| 3859.47 | 0 | | 4141.41 | 0 | FeIII ? |
| 3867.47 | 3 | HeI(20) | 4143.78 | 7 | HeI(53) |
| 3868.91 | 1 | | 4155.87 | 1 | FeIII ? |
| 3870.16 | 1 | | 4168.39 | 0 | HeI(52) |
| 3871.84 | 3 | HeI(60) | 4172.36 | 0 | |
| 3878.20 | 1 | HeI(59) | 4186.62 | 0 | FeIII |
| 3888.80 | 25 | HeI and H8 | 4222.45 | 0 | FeIII |
| 3901.72 | 2 | | 4225.55 | 0 | FeIII |
| 3904.68 | 1 | | 4229.76 | 0 | |
| 3914.03 | 0 | | 4240.78 | 0 | FeIII |
| 3926.60 | 5 | HeI(58) | 4244.39 | 1 | FeIII |
| 3927.73 | 2 | | 4248.41 | 1 | FeIII ? |
| 3928.84 | 1 | | 4256.02 | 1 | |
| 3929.68 | 2 | | 4266.24 | 2 | FeIII |
| 3931.16 | 3 | | 4269.37 | 1 | |
| 3932.48 | 2 | | 4274.48 | 1 | |
| 3933.65 | 3 | CaII(1) | 4340.57 | 18 | Hγ |
| 3935.86 | 1 | HeI(57) | 4352.45 | 3 | FeIII(4) |
| 3939.79 | 0 | | 4366.18 | 1 | FeIII(4) |
| 3954.42 | 1 | FeIII(120) | 4372.03 | 2 | FeIII(4) |
| 3960.08 | 0 | | 4380.76 | 0 | |
| 3964.71 | 12 | HeI(5) | 4382.27 | 0 | FeIII(4) |
| 3968.48 | 1 | FeIII(120 and CaII(1) | 4388.03 | 9 | HeI(51) |
| | | | 4391.54 | 0 | FeIII(42) |
| 3970.08 | 19 | Hε | 4395.91 | 2 | FeIII(4) |
| 3997.39 | 0 | | 4397.70 | 1 | |
| 4000.76 | 0 | FeIII | 4399.95 | 1 | |
| 4004.98 | 2 | FeIII | 4402.05 | 0 | |
| 4009.52 | 5 | HeI(55) | 4408.09 | 0 | |
| 4023.90 | 2 | HeI(54) | 4412.13 | 1 | |
| 4026.21 | 13 | HeI(18) | 4415.72 | 1 | |
| 4047.44 | 0 | | 4419.58 | 4 | FeIII(4) |
| 4052.14 | 0 | | 4427.46 | 2 | NII(56) |
| 4054.29 | 0 | | 4430.96 | 3 | FeIII(4) |
| 4055.38 | 0 | | 4434.79 | 1 | |
| 4066.92 | 1 | NiII(11) | 4437.87 | 2 | HeI(50) |
| 4070.15 | 1 | FeIII ? | 4456.52 | 0 | |
| 4071.66 | 0 | NiII(11) | 4471.65 | 15 | HeI(14) |
| 4078.92 | 2 | | 4476.80 | 1 | |
| 4086.85 | 0 | | 4480.19 | 0 | |
| 4092.61 | 0 | FeIII | | | |

Table III (Cont.)

| Wavelength | Intensity | Identification |
|---|---|---|
| 4490.50 | 1 | |
| 4502.96 | 0 | |
| 4509.70 | 1 | |
| 4515.55 | 2 | |
| 4520.80 | 0 | |
| 4540.70 | 0 | |
| 4555.27 | 1 | |
| 4567.60 | 0 | |
| 4697.27 | 3 | |
| 4713.27 | 7 | HeI(12) |
| 4751.80 | 3 | |
| 4861.36 | 12 | Hβ |
| 4879.75 | 0 | |
| 4899.17 | 3 | |
| 4906.40 | 1 | |
| 4921.70 | 5 | HeI(48) |
| 5015.47 | 4 | HeI(4) |
| 5048.21 | 2 | HeI(47) |
| 5063.73 | 0 | FeIII(5) |
| 5073.50 | 0 | FeIII(5) |
| 5086.80 | 0 | FeIII(5) |
| 5126.16 | 2 | FeIII(5) |
| 5156.81 | 1 | FeIII(5) |
| 5193.82 | 0 | FeIII(5) |
| 5198.02 | 1 | |
| 5213.19 | 1 | |
| 5219.90 | 0 | |
| 5326.38 | 0 | |
| 5332.31 | 1 | |
| 5345.27 | 2 | |
| 5376.22 | 0 | FeIII |
| 5434.11 | 1 | |
| 5444.40 | 0 | FeIII(110) ? |
| 5551.71 | 2 | |
| 5652.96 | 1 | |
| 5777.66 | 0 | |
| 5846.56 | 0 | |
| 5876.47 | 5 | HeI(11) |
| 5932.47 | 0 | NII(28) |
| 5942.34 | 0 | NII(28) |
| 5993.31 | 1 | |
| 6026.98 | 1 | |
| 6140.04 | 0 | |
| 6152.10 | 0 | |
| 6207.67 | 2 | |
| 6226.45 | 0 | |
| 6410.65 | 2 | |
| 6514.97 | 2 | |
| 6562.49 | 0 | Hα |

TABLE IV

GAMMA CASSIOPEIAE

SPECTRUM 1946

| λ | EM | ABS | Identification |
|---|---|---|---|
| 3934 | | x | HeI(57)+CaII(1) |
| 3964 | | x | HeI(5) |
| 3970 | | x | Hε |
| 4009 | | x | HeI(55) |
| 4026 | | x | HeI(18) |
| 4043 | | x | NII(39) |
| 4070 | | x | OII(10) |
| 4089 | | x | SiIV |
| 4101 | | x | Hδ |
| 4118 | | x | SiIV + OII(20) |
| 4131 | | x | SiII(3) |
| 4144 | | x | HeI(53) |
| 4301 | x | | FeII(27) |
| 4318 | | x | OII(2) |
| 4388 | | x | HeI(58) |
| 4415 | | x | OII(5) |
| 4471 | | x | HeI(14) |
| 4640 | | x | OII(1) |
| 4649 | | x | OII(1) + CIII(1) |
| 4840 | x | | |
| 4861 | x | x | Hβ |
| 4932 | | x | HeI(48) |
| 4935 | x | | |
| 5015 | | x | HeI |
| 5057 | x | | SiII(5) |
| 5875 | x | | HeI |
| 6370 | | x | SiII(2) |
| 6562 | x | | Hα |
| 4340 | | x | Hγ |

TABLE V

SPECTRUM

1947 - 1954

| Wavelength | | Wλ | Width v km/sec | r | Width Δλ | Identification |
|---|---|---|---|---|---|---|
| 3771 | ab | 0.63 | 850 | 0.88 | 5.2 | Hl1 |
| 3798 | ab | 1.03 | 940 | 0.84 | 5.9 | SiIII(5) and Hl0 |
| 3807 | ab | | | | | SiIII(5) |
| 3820 | ab | 0.53 | 560 | 0.88 | 4.2 | HeI |
| 3835 | ab | 1.16 | 1150 | 0.83 | 6.3 | H9 |
| 3882 | ab | | | | | OII(2) |
| 3889 | ab | 1.41 | 1310 | 0.84 | 5.9 | H8 and HeI |
| 3912 | ab | | | | | OII(17) |
| 3919 | ab | | | | | CII(4) and OII(17) |
| 3927 | ab | 0.34 | 580 | 0.92 | 5.0 | HeI(58) |
| 3970 | ab | 1.70 | 1480 | 0.78 | 5.7 | Hε |
| 3983 | ab | | | | | Oll(6) |
| 3995 | ab | | | | | NII(12) |
| 4009 | ab | 0.34 | 610 | 0.92 | 4.6 | HeI(55) |
| 4026 | ab | 0 59 | 650 | 0.88 | 4.9 | HeI(18) |
| 4067 | ab | 0.45 | 730 | 0.93 | 6.9 | CIII(16) |
| 4070-4072 | ab | 0.58 | 790 | 91 | 7.5 | OII(10) |
| 4076 | ab | | | | | OII(10) |
| 4041-4044 | ab | | | | | NII(39) |
| 4089 | ab | 0.54 | 670 | 0 91 | 6.5 | SiIV |
| 4101 | ab | 1.98 | 1650 | 0.84 | 11.6 | Hδ |
| 4118 | ab | 0.56 | 680 | 0.92 | 6.6 | SiIV and OII(20) |
| 4144 | ab | 0.45 | 670 | 0.92 | 6.5 | HeI(53) |
| 4153 | ab | 0.56 | 580 | 0.89 | 4.7 | OII(19) and SII |
| 4185 | ab | | | | | OII(36) and CIII ? |
| 4254 | ab | | | | | SIII |
| 4267 | ab | | | | | CII(6) |
| 4285 | ab | | | | | SIII |
| 4318 | ab | 0.31 | | | | OII(2) |
| 4340 | ab | 2.32 | 1900 | 0.93 | 20. | Hγ |
| 4367 | ab | | | | | OII(2) |
| 4388 | ab | 0.51 | 720 | 0.92 | 7.1 | HeI(51) |
| 4416 | ab | 0.38 | 630 | 0.93 | 6.3 | OII(5) |
| 4471 | ab | 0.79 | 850 | 0.89 | 7.8 | HeI(14) |
| 4640 | ab | 0.54 | 555 | 0.90 | 5.3 | OII(1) |
| 4649 | ab | 0.85 | 650 | 0.88 | 6.5 | CIII(1) and OII(1) |
| 4861 | ab & em | 1.46 | 650 | 1.32 | 6.8 | Hβ |
| 5876 | em | 1.48 | 810 | 1.2 | 11.7 | HeI |
| 6563 | em | 13.9 | 1180 | 2.4 | 9.4 | Hα |

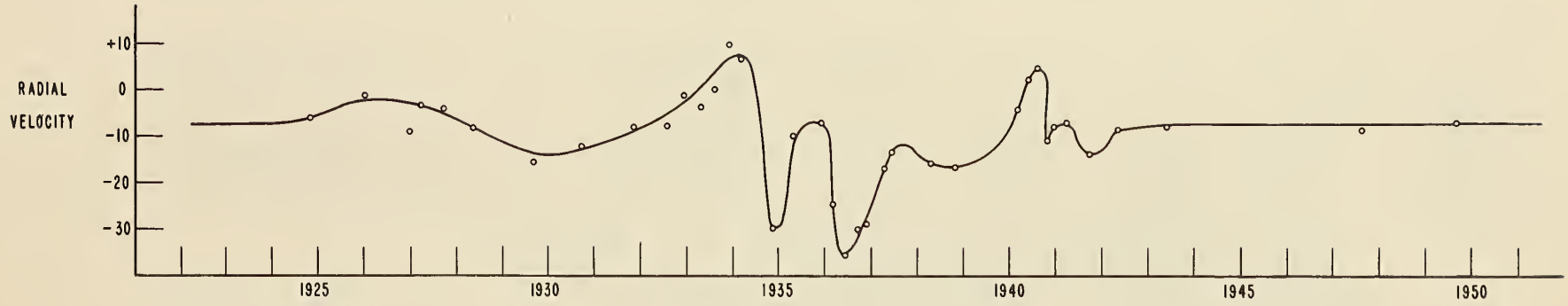



Figure 1

VISUAL
MAGNITUDE
1.50
1.75
2.00
2.25
2.50
2.75
3.00
1925
1930
1935
1940
1945
1950

Figure 2

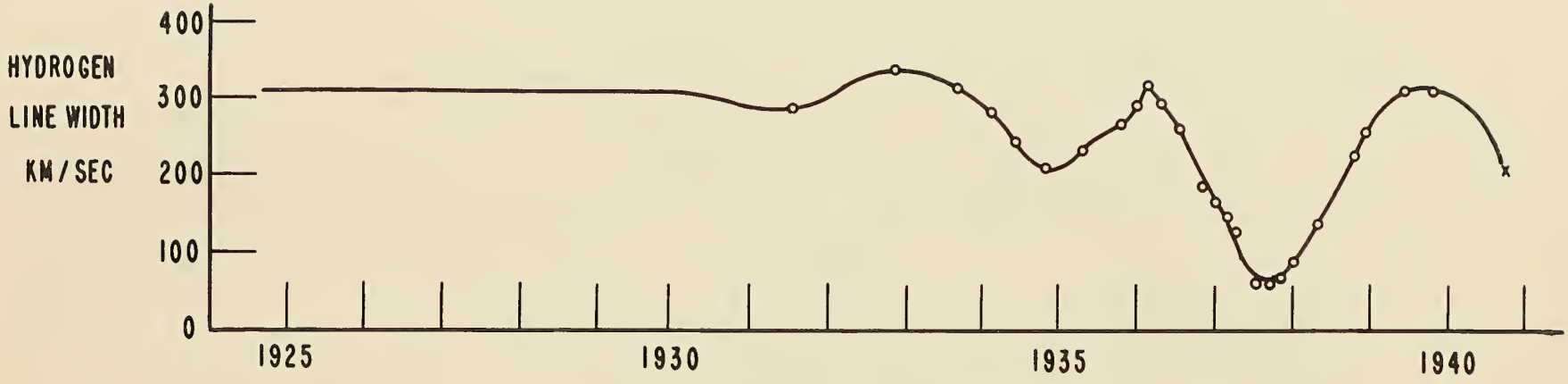

HYDROGEN
LINE WIDTH
KM / SEC
400
300
200
100
0
1925
1930
1935
1940

Figure 3

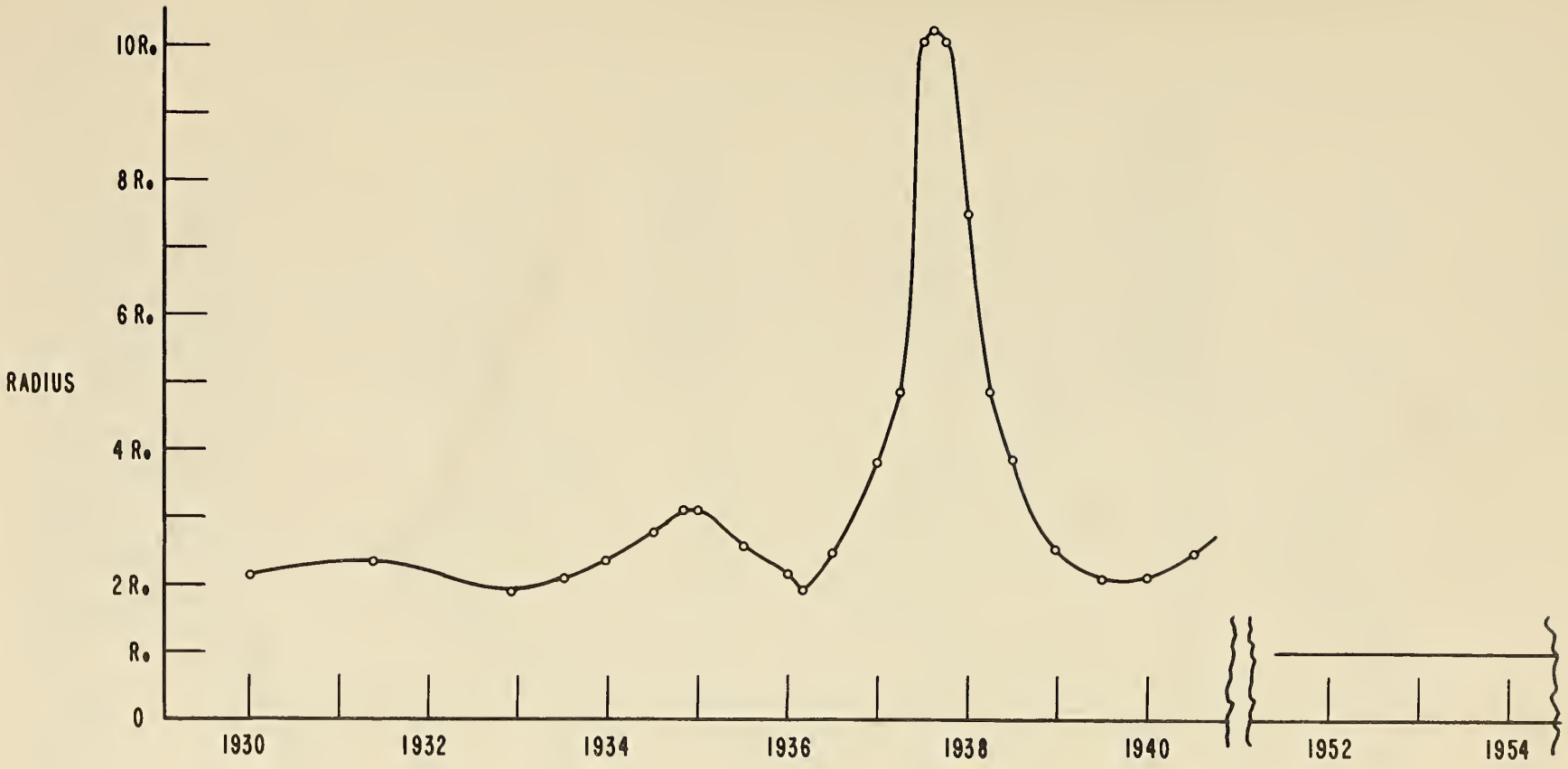
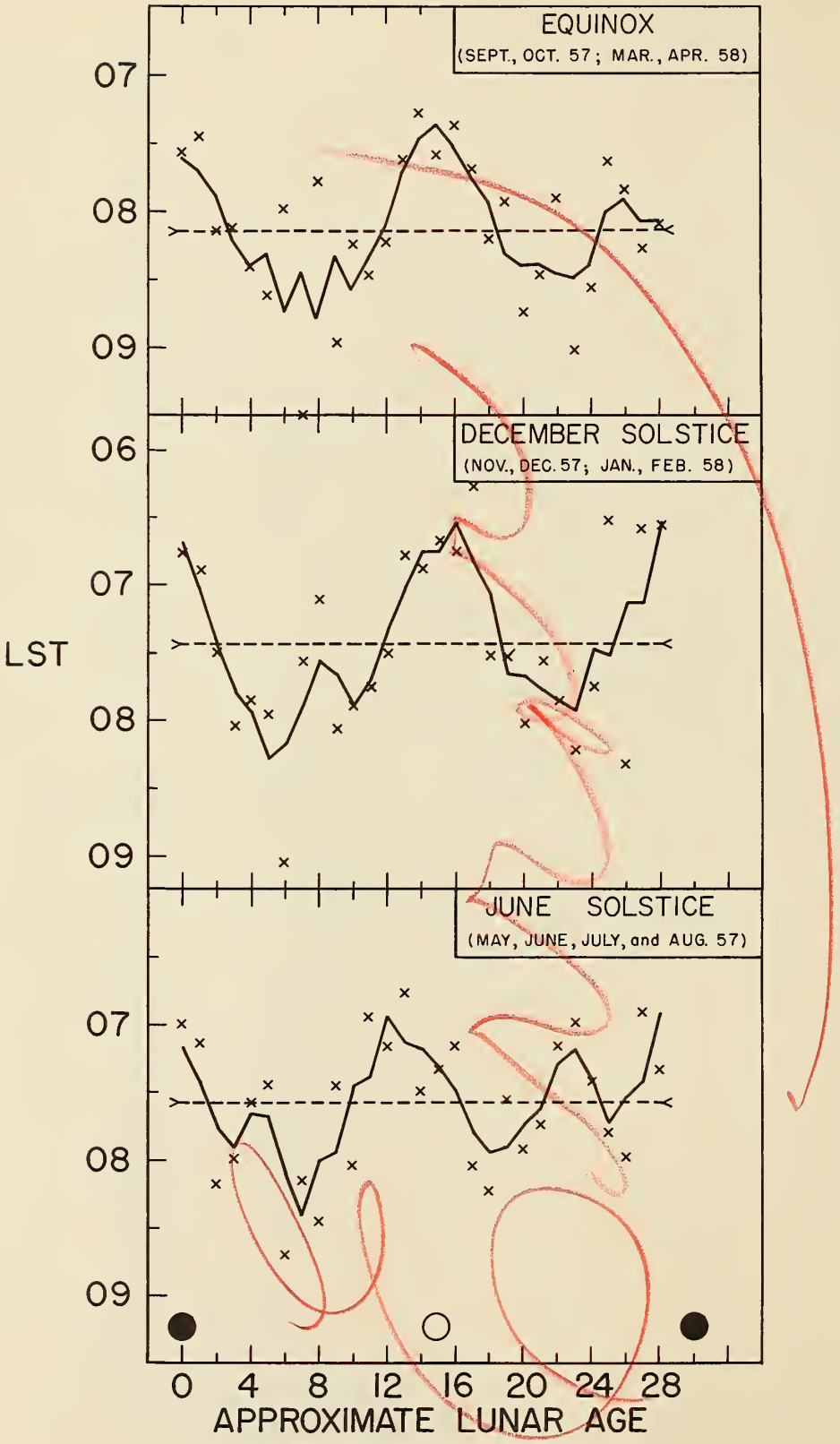

10R.
8 R.
6 R.
RADIUS
4 R.
2 R.
R.
0
1930
1932
1934
1936
1938
1940
1952
1954

Figure 4




LUNAR INFLUENCE ON
TIME OF FIRST APPEARANCE OF Es-q
AT HUANCAYO (Three-day running mean plotted)

Figure 5

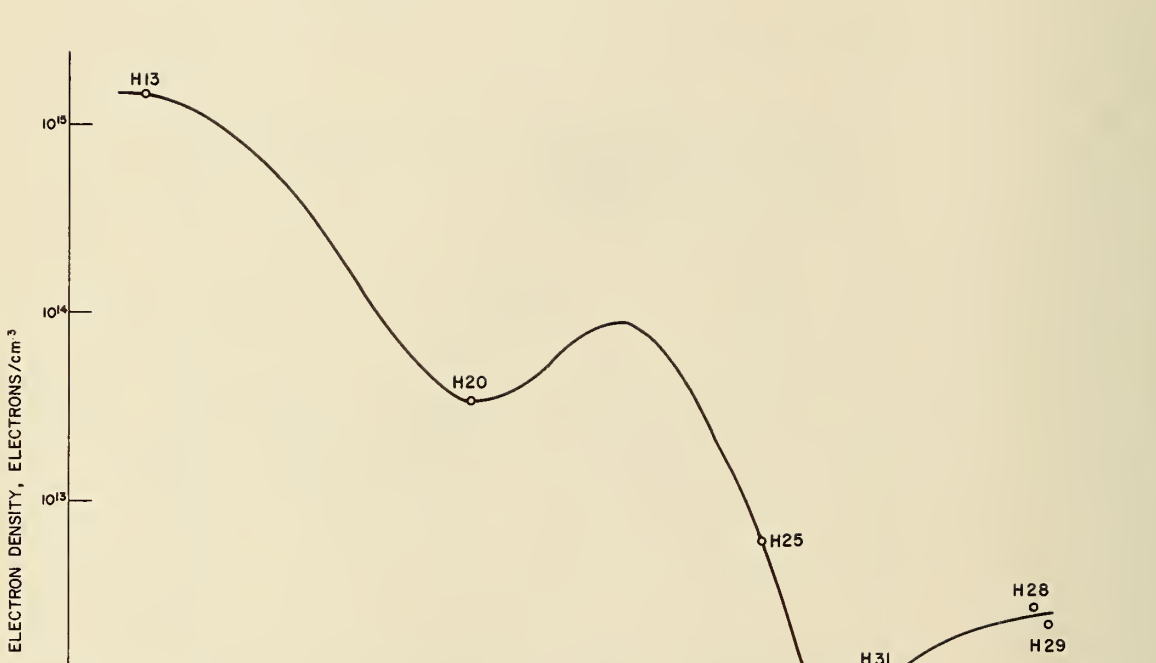

H13
H20
H25
H28
H29
H31
H 34
ELECTRON DENSITY, ELECTRONS/cm³
10¹⁵
10¹⁴
10¹³
10¹²
10¹¹
1932
1933
1934
1935
1936
1937
1938
1939

FIGURE 5

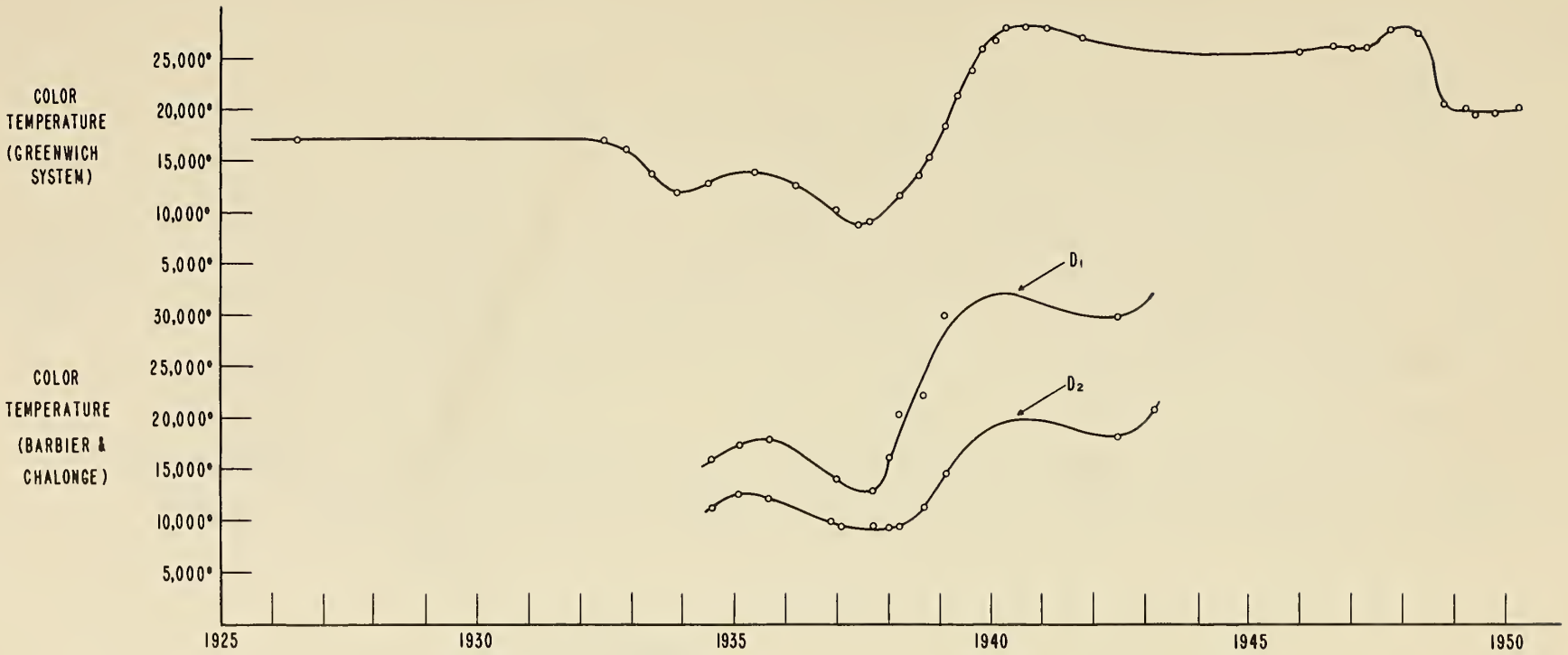

COLOR TEMPERATURE (GREENWICH SYSTEM)
25,000°
20,000°
15,000°
10,000°
5,000°
COLOR TEMPERATURE (BARBIER & CHALONGE)
30,000°
25,000°
20,000°
15,000°
10,000°
5,000°
D1
D2
1925
1930
1935
1940
1945
1950

Figure 6

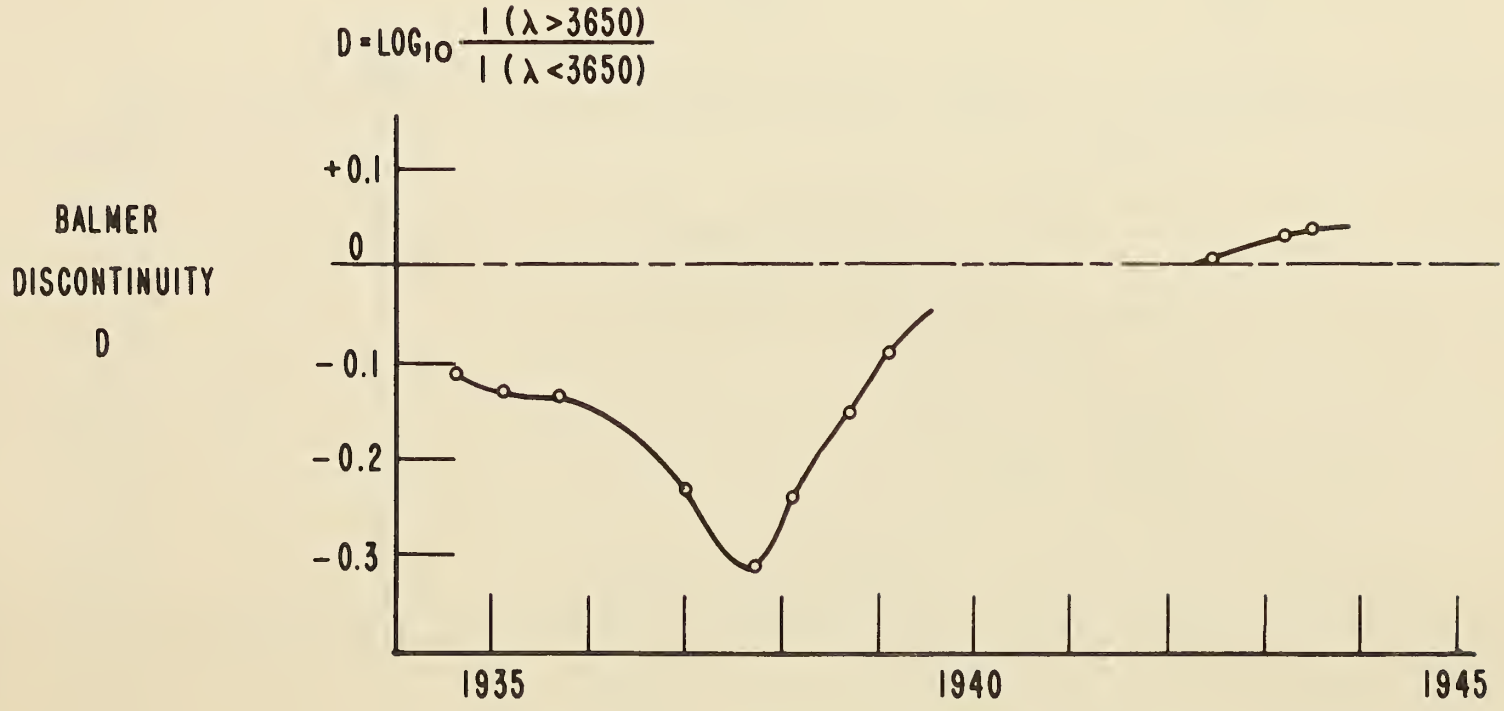

$D = \log_{10} \frac{I(\lambda > 3650)}{I(\lambda < 3650)}$
BALMER
DISCONTINUITY
D
+0.1
0
-0.1
-0.2
-0.3
1935
1940
1945

Figure 7

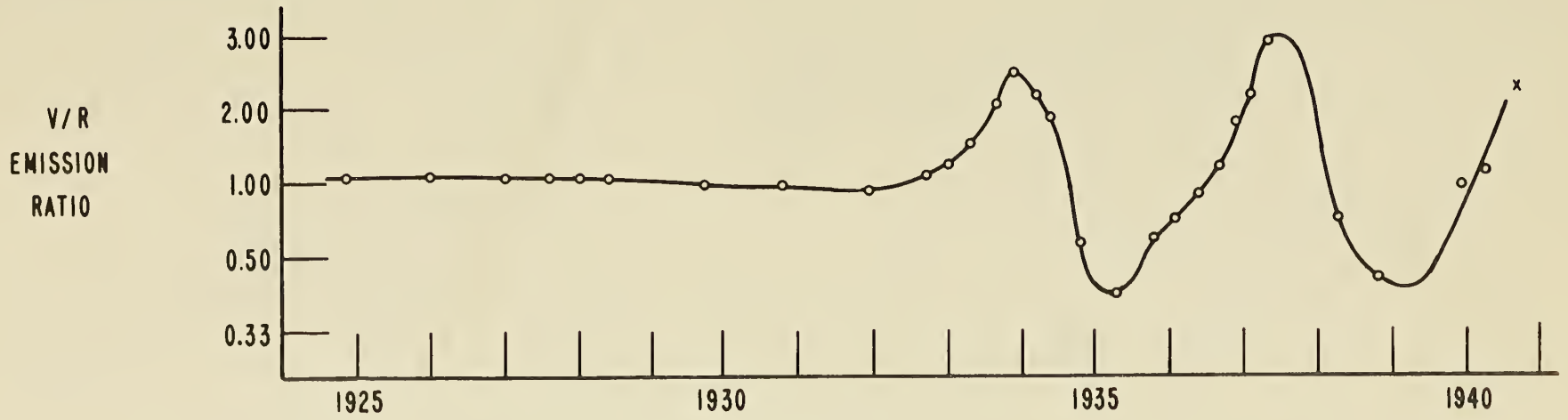



Figure 8

U.S. DEPARTMENT OF COMMERCE
Frederick H. Mueller, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

# THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

## WASHINGTON, D.C.

**Electricity and Electronics.** Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

**Optics and Metrology.** Photometry and Colorimetry. Photographic Technology. Length. Engineering Metrology.

**Heat.** Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Molecular Kinetics. Free Radicals Research.

**Atomic and Radiation Physics.** Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

**Chemistry.** Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

**Mechanics.** Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

**Organic and Fibrous Materials.** Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

**Metallurgy.** Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

**Mineral Products.** Engineering Ceramics. Glass. Refractories. Enameled Metals. Constitution and Microstructure.

**Building Technology.** Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer. Concreting Materials.

**Applied Mathematics.** Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

**Data Processing Systems.** SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Application Engineering.

- Office of Basic Instrumentation.
- Office of Weights and Measures.

## BOULDER, COLORADO

**Cryogenic Engineering.** Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

**Radio Propagation Physics.** Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Radio Warning Services. Airglow and Aurora. Radio Astronomy and Arctic Propagation.

**Radio Propagation Engineering.** Data Reduction Instrumentation. Modulation Research. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation Obstacles Engineering. Radio-Meteorology. Lower Atmosphere Physics.

**Radio Standards.** High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

**Radio Communication and Systems.** Low Frequency and Very Low Frequency Research. High Frequency and Very High Frequency Research. Ultra High Frequency and Super High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Systems Analysis. Field Operations.

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