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RADIAL VELOCITIES AND SPECTRAL CHARACTERISTICS OF THE POPULATION II CEPHEIDS M5 NO. 42, M5 NO. 84, AND TW CAPRICORNI*

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ABSTRACT

Radial velocity-curves have been obtained for three population II cepheids with periods close to 27 days. Double lines have been observed for M5 No. 42 and TW Capricorni, and it is shown that the velocity-curves of all population II cepheids of period greater than 15 days are probably discontinuous. The spectral changes of the three program stars are described and compared with standards on the Yerkes system of classification, the classical cepheid T Monocerotis, and other population II cepheids. These three stars have an early spectral type at maximum, A5-A6 Ib-II and get no later than F5. Hydrogen emission is present during increasing light but is not so strong as in W Virginis. Among the population II cepheids of period greater than 15 days there seems to be a correlation between earliest spectral type and shape of the light-curve. The general weakness of the hydrogen lines in absorption can be interpreted as meaning either that incipient emission is generally present or that the hydrogen-to-metal ratio is considerably higher than for standard stars.

I. INTRODUCTION

Recent photometric studies of the population II cepheids (Arp 1955, 1957) have made desirable a concentrated spectroscopic effort on several of these stars. The variables in M5 were chosen for study because not only are they the brightest of the variables in globular clusters but they also have certain interesting properties. Number 42 has a light-curve that differs from W Virginis in that the shoulder on the declining branch occurs later and the star is considerably bluer. The light curve of No. 84 alternates between deep and shallow minima and hence is an RV Tauri star. Both stars in M5 lie on the uppermost line in Arp's period-luminosity diagram. TW Capricorni was chosen in order to study a field star of similar period, 28.5 days. Its light-curve (S. Gaposchkin 1952) is similar to that of M5 No. 42.

II. LIGHT-CURVES AND PHASES

Although only a short time has passed since Arp's photometric studies, it seemed best in 1956 to redetermine the light-curves of the variables in M5 in order to be entirely sure of the phases of the spectroscopic observations and to be sure that the form of the light-curve has not changed in the intervening time. The new Cassegrain spectrograph on the Mount Wilson 60-inch telescope is equipped with a direct plateholder that can be placed in position very easily. However, it holds only a 4 × 5-inch plate, and at the Cassegrain focus this permits only a very small field to be taken at one time. The M5 stars are so bright in the blue that no comparable stars were available in the field, and no attempt was made to obtain light-curves in this color. In the visual region a sequence of six stars was established in the inner part of the cluster. Even in the visual region the brightest comparison star of the sequence was 1 mag. fainter than the variables at maximum light. The light-curves obtained were not of as good quality as those of Arp (1955) and so need not be reproduced here. The phases were well determined, however.

Number 42 showed no change in behavior, and the ephemeris of Arp (1955) was

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found to hold; No. 84 continued to show alternation at minimum of the same magnitude as before. Combination of the observed maximum of No. 84 with that observed in 1952 yields a period of 26.54 days, which is so close to one of Arp's (1955) suggested periods, 26.531 days, that the latter can now be considered as established. Arp's 1954 observations (1957) do not conform to this, so evidently the star misbehaved rather badly in 1954.

In order to determine the phase in 1956 of TW Capricorni, Mr. Thomas Cragg kindly made a series of visual observations with the Mount Wilson 6-inch refractor. By observing the star on the rapidly rising branch of the light-curve, Cragg obtained a good epoch of maximum, JD 2435636.6 \pm 1, which combines with Gaposchkin's (1952) maximum to yield a period of 28.556 days.

III. RADIAL VELOCITIES

a) *The Observations*

Almost all the observations were taken with the new Cassegrain spectrograph of the 60-inch telescope. Cameras of focal length 4 and 8 inches were employed, giving dispersions of 80 and 40 Å/mm, respectively. When looking for double lines near light-maximum, the 16-inch camera was used to obtain 20 Å/mm. In addition, Drs. Greenstein and Münch obtained three plates at the coudé spectrograph of the 200-inch telescope. These plates have a dispersion of 18 Å/mm.

The choice of lines measured for velocity depended upon the dispersion. Laboratory wave lengths were used, and a few seemingly unblended lines were discarded because of large residuals. The probable error for the mean velocity of a plate is about 4 km/sec at 80 Å/mm and 2 km/sec at 40 Å/mm.

b) *The Velocity-Curves Drawn Continuously*

The drawing of velocity-curves depends upon the presence or absence of double lines near light-maximum. These are not resolvable with a dispersion of less than 20 Å/mm. Since most population II cepheids are so faint that high-dispersion plates are an impossibility with present equipment, it seems best first to discuss these three stars from the point of view of continuous velocity-curves, even if double lines have been observed. Since future work on fainter variables will be limited to low dispersion, comparisons can then be made with the continuous velocity-curves shown here for the brighter stars. The velocity-curves of No. 42, No. 84, and TW Capricorni are shown in Figures 1-3.

Number 42 shows a smooth curve, which correlates with the regularity of its light-curve. The falling branch of the velocity-curve is very rapid, corresponding to the rapid rise in the light-curve. The velocity amplitude is 40 km/sec.

The RV Tauri star, No. 84, shows behavior strikingly different from that of No. 42, which is in the same cluster and has almost the same period. Odd and even cycles are drawn separately in Figure 2. There is a different of about 0.3 in the phase of the falling branch. There seems to be no doubt that this is real. It was strongly suspected on the basis of the 1956 observations and was confirmed by two plates specially taken on each of two successive cycles in March and April, 1957. When the velocity declines late, the secondary maximum in the light-curve is strong. That is, after a deep minimum the new wave or surge of gas is late in arriving at the star's atmosphere, and, correspondingly, a shallow minimum is followed by the early arrival of the new wave. The velocity amplitude is 40 km/sec in a shallow minimum and 60 km/sec in a deep minimum.

Although there are a large number of plates available of TW Capricorni, the curve is poorly determined, probably because of poor repetition from cycle to cycle. This non-repetition is not a regular alternation of odd and even cycles as it is for M5 No. 84. The velocity amplitude is about 40 km/sec.

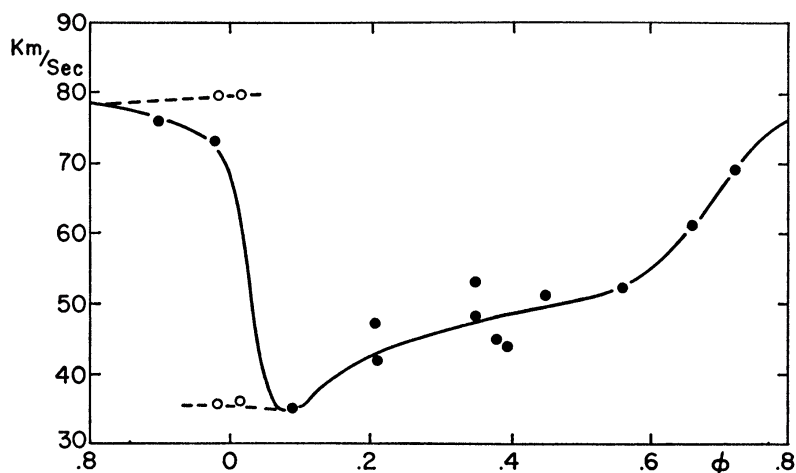


FIG. 1.—Velocity-curve of M5 No. 42. Open circles are from plates showing double lines

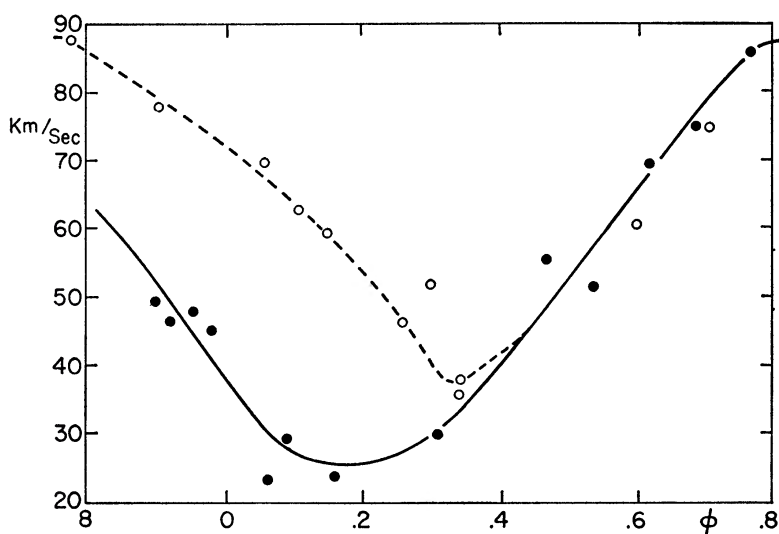


FIG. 2.—Velocity-curve of M5 No. 84. Filled circles are from even cycles (deep minimum) and open circles are from odd cycles (shallow minimum).

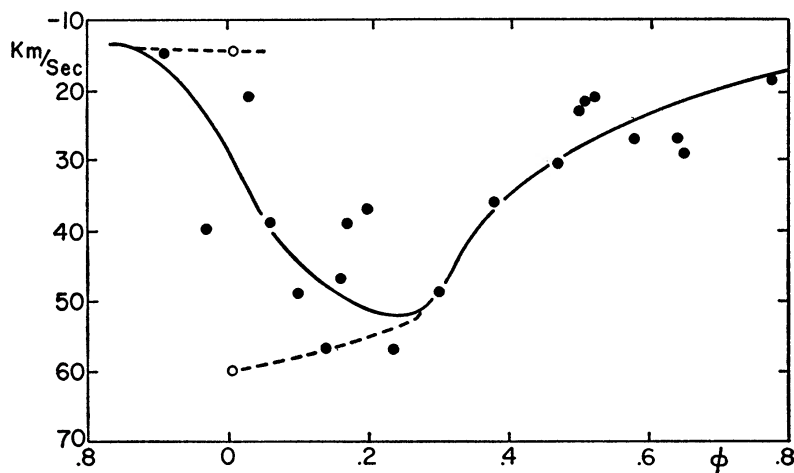


FIG. 3.—Velocity-curve of TW Capricorni. Open circles are from the plate showing double lines

c) *Double Lines and Discontinuous Velocity-Curves*

It is at this point that the presence of double lines must be discussed. Their presence in W Virginis is well known, and they may be considered as one of the important differences between population II and classical cepheids. The presence of double lines in the classical cepheid X Cygni has been reported by Kraft (1956), but the appearance of the spectrum at the phase of doubling is completely different.

There is no question as to the presence of double lines for M5 No. 42. They were first noted on plate Xd 1417, which required an exposure of 14 hours at the 60-inch. This was done on two nights, during which the total change in phase was 0.05, which is sufficiently short. Palomar plate Pd 2635, obtained by Münch, is of excellent quality and shows that nearly all strong unblended lines are double.

Double lines appear on one plate of TW Capricorni, Xd 1823, obtained in 9 hours on two nights on Mount Wilson. The presence of double lines does not assist in drawing a mean curve through the badly scattered points.

In Figures 1 and 3 the velocities of the doubled lines are shown as open circles, and the discontinuous velocity-curves are shown as dotted lines.

TABLE 1
RATIOS OF RESIDUAL CENTRAL INTENSITIES OF DOUBLE LINES

Element	No Lines	Mean V/R	Element	No Lines	Mean V/R
Fe I..	10	0 80	Ti II.	13	1 04
Fe II	6	0 94	Sr II	2	1 12

Two Palomar plates of No. 84 fail to show double lines. Pd 2587 was taken at the phase (0.11 of a late decline) at which they are to be expected. Unfortunately, a late decline should show a smaller amplitude of doubling, and an attempt to get a Palomar plate on the other cycle was frustrated by the weather. The lines of Pd 2587 are extremely broad but are not double. Now Abt (1955) in his study of the RV Tauri star U Monocerotis found line doubling of only about 35 km/sec. This would be at the very limit of detectability at 18 A/mm, especially if the lines had appreciable intrinsic width.

It is important to see whether or not the presence of double lines can be detected at lower dispersion. With this in mind, plate Pd 2635 of No. 42 with clearly double lines was studied spectrophotometrically. Rather than go through a full curve-of-growth analysis for a single plate, the following semiquantitative procedure was used. For lines that appeared double and relatively unblended, the residual intensity at the center of each component of the line was measured. This was done for Fe I, Fe II, Ti II, and Sr II. In Table 1 is tabulated V/R , where V is the residual intensity at the center of the violet component and R is the residual intensity at the center of the red component.

The steady increase in V/R as we go from Fe I to Sr II is the same as saying that for Fe I the violet component is stronger, while for Sr II the red component is stronger. This means that at this phase there should appear on plates of moderate dispersion a velocity difference between Fe I and either Sr II or Ti II. This very difference has been detected in the classical cepheids T Monocerotis and SV Vulpeculae by Sanford (1956). Possibly the absorption lines of these stars are actually double but are so badly broadened and blended that only these velocity differences can be detected on the plate.

For the population II cepheids it seems best to compare Fe I and Ti II, since there are not a sufficient number of lines of Sr II to form a mean velocity with a small probable error. At a dispersion of 80 A/mm the effect is lost in the random error of measurement, but at 40 A/mm the accuracy of measurement is great enough to detect differ-

ences of about 5 km/sec. Plate Xe 1585 of No. 84, taken at phase 0.98 following a shallow minimum (i.e., when a large amplitude of doubling is expected), shows a difference of 15 km/sec between the velocities of the Fe I and Ti II lines. At other phases the velocity differences between Ti II and Fe I are never more than 5 km/sec. It seems likely that the effect is due to the presence of double lines near light-maximum and not to a level effect such as appears to be present at AC Herculis at all phases (Sanford 1931).

It is now worthwhile summarizing which population II cepheids have double lines. In the general field W Virginis and TW Capricorni have double lines. Also the RV Tauri stars U Monocerotis and AC Herculis have double lines. In the globular clusters, M5 No. 42 definitely has double lines, and the RV Tauri star M5 No. 84 probably has double lines. From this it seems very likely that all population II cepheids of period greater than about 15 days have double lines.

IV. CLASSIFICATION AND DESCRIPTION OF THE SPECTRA

The spectra were compared with standards listed by Johnson and Morgan (1953). The population II cepheids are peculiar and cannot be fitted uniquely into the Yerkes system of classification. The hydrogen lines appear in emission during increasing light and are weak and perhaps partially filled by incipient emission during the rest of the cycle. Since the hydrogen lines are particularly important in the classification of F stars, this makes classification difficult. For these stars I have not used the hydrogen lines at all but rather have determined the spectral types by the strength of Fe I, Ca I, and Cr I, and, for types F0 and earlier, Ca II. The luminosity class was determined largely by the strength of Ti II, since neither Sr II nor Fe II gives consistent results from one star to another.

The general property of the spectra of population II cepheids will be discussed first, followed by a description of the spectra of the three program stars.

a) Population II Cepheids in General

For comparison purposes, spectra of the classical cepheid T Monocerotis were classified from plates taken with the same spectrograph. In addition, a few spectra of other population II cepheids of various periods were taken and classified. It was also helpful to classify the best of the plates in the Mount Wilson Observatory files. These were taken largely by Dr. Joy. The data for T Monocerotis and fifteen population II cepheids are summarized in Table 2.

After T Monocerotis are listed the cepheids in the clusters, followed by the field stars. Within each group the stars are listed according to period. No serious differences between the stars in clusters and the field stars can be seen. There seems to be little, if any, correlation of spectral type with period. Emission seems to have a marked maximum among stars of period 15–19 days. Emission is definitely weaker among the stars of period 20–30 days.

Among the stars of period greater than 15 days a marked correlation between spectral type and light-curve is present. Stars with a light-curve similar to W Virginis, i.e., with a high shoulder just after maximum, are at spectral type F0 at the earliest. On the other hand, stars with the shoulder occurring late reach type A5–A8 just before maximum light. These can be called TW Capricorni stars, to differentiate them from the W Virginis type. This separation on the basis of early spectral type was recognized before the spectra of M10 No. 2 and M3 No. 154 were taken. One plate of each of these stars was then taken at the proper phase, i.e., just before maximum light; and the two stars showed spectra as expected. The four TW Capricorni stars in the clusters lie on the uppermost of the three lines in Arp's period-luminosity diagram.

There are several stars that are barely bright enough for spectra to be taken that should definitely prove this correlation between spectral type and light-curve. They

are all in the Southern Hemisphere. On the basis of light-curves published by Mrs. Payne-Gaposchkin (1956), the following stars should belong to the W Virginis group: UX Lupi, RX Librae, and RV Normae. On the other hand, the light-curve of V1077 Sagittarii indicates that it should be of the TW Capricorni type. The published light-curves of ST Puppis and RR Microscopii (S. Gaposchkin 1957) are indecisive, and a photometric and spectroscopic study of these stars by Southern Hemisphere observers would be worthwhile. ST Puppis is brighter than W Virginis by almost a magnitude.

b) The Spectra of No. 42, No. 84, and TW Capricorni

Before describing and illustrating the details of the spectra of the three stars under consideration, it seems worthwhile to describe the spectrum of the classical cepheid of similar period, T Monocerotis, and the population II cepheid which has been studied at high dispersion, W Virginis (Abt 1954). These descriptions are based on plates taken with the same equipment as that used for No. 42, No. 84, and TW Capricorni.

TABLE 2
SPECTRAL TYPES AND EMISSION INTENSITIES OF CEPHEIDS

Star	Period (days)	Earliest Spectrum	Latest Spectrum	Hydrogen Emission	Remarks
T Mon...	27	F8	K0	No	Typical classical cepheid; see discussion
M2 No. 11	34	A8	G0	Present	Spectrum might get later than G0 during a deep minimum
M5 No. 84	27	A5	F5	Present	See discussion
M5 No. 42	26	A6	F5	Present	See discussion
M10 No. 2	19	F0	G0	Strong	
M3 No. 154	15	A6	G0	Strong	
M13 No. 2	5.1	A8	F8	No	
M13 No. 1	1.5	A2	F0	No	
TW Cap	29	A5	F4	Present	See discussion
MZ Cyg.....	21	F5	G5	?	
W Vir	17	F0	G0	Very strong	See discussion
AP Her.	10	F0	F5	No	Spectral range may be greater
AL Vir.	10	F0	F8	No	
CN Lyr	2.3	F0	F5	No	Spectral range may be greater
UY Eri.	2.2	A5	F2	No	
BL Her	1.3	A6	F3	?	

The spectrum of T Monocerotis was found to vary from F8 *Iab* to K0 *Ib* about as described by Code (1947). The effects described by Struve (1944) are easily recognizable on these plates. The hydrogen lines are as strong as F0 at maximum light, and certain ionized lines are abnormally strong just before maximum.

The spectrum of W Virginis varies from F0 *Ib* at light-maximum to G0 *Ib* at light-minimum. Hydrogen emission lines are extremely strong and last from phase 0.70 to 0.10. At other phases, hydrogen is weak for its spectral class, and incipient emission may be present. Helium emission at λ 4472 was originally suspected on one plate by Joy. Helium emission at λ 5876 was found by Kraft on two plates (originally taken by Sanford) in the Mount Wilson Observatory files. The spectrum does not appear too different from the standards, although the absorption lines are generally weak. Mg II λ 4481 is generally quite weak. If the luminosity class *Ib* is assigned on the basis of the strength of Fe II and Ti II, then Sr II is much too weak. This was noted by Abt and interpreted as

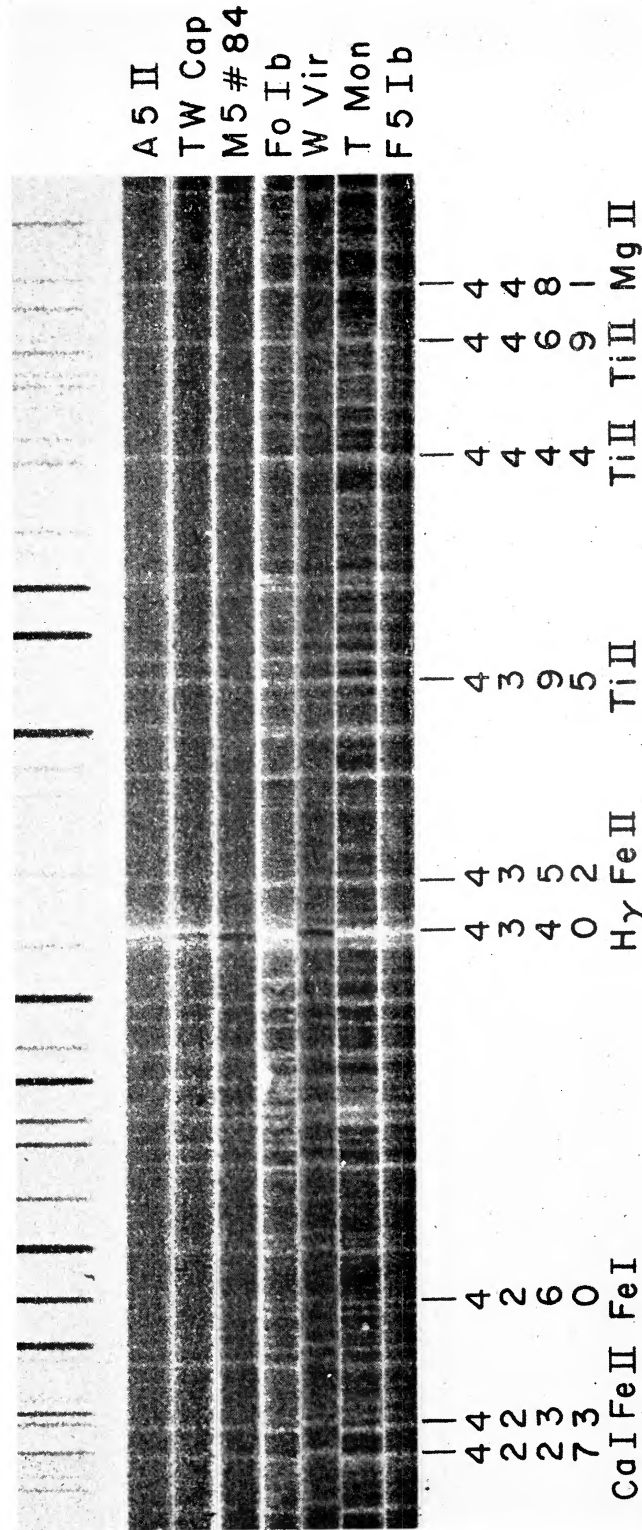


FIG. 5.—Spectra of cepheids and comparison stars near maximum light; original dispersion, 40 Å/mm

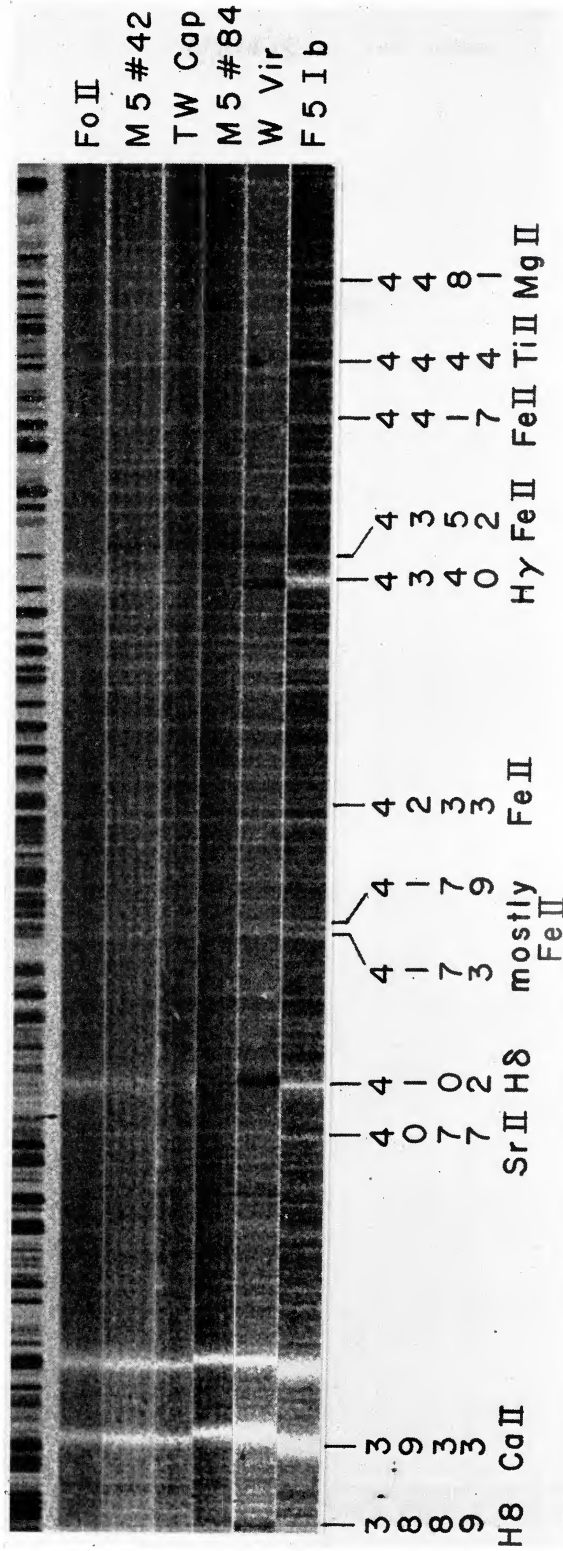


FIG. 6.—Spectra of cepheids and comparison stars during increasing light; original dispersion 80 Å/mm

an abundance difference by a factor of 5. The weakness of Sc II, which Abt found to be underabundant by a factor of 3, is barely noticeable.

The spectral type at M5 No. 42 reaches type A6 Ib-II just before maximum light and declines to F5 by phase 0.35, but gets no later. Hydrogen emission lasts from about 0.80 to 0.07. Hydrogen absorption is generally weak for the spectral type. The following lines are listed in order of their weakness—for the assigned spectral type—the weakest being listed first: Mg II λ 4481; Sc II λ 4320; Fe I λ 4260; Mn I $\lambda\lambda$ 4030–4034; and several Fe II lines.

M5 No. 84 reaches type A5 Ib-II just before light-maximum and also declines rapidly to about F5 but remains there or even becomes a little earlier through minimum. Hydrogen is in emission from 0.80 to about 0.20. Weak lines are Mg II λ 4481; several Fe II lines; Fe I λ 4260; and Mn I $\lambda\lambda$ 4030–4034. Neither Sr II nor Sc II is weak in this star.

TW Capricorni varies from A5 Ib just before maximum to F4 Ib by phase 0.38, after which it slowly becomes earlier. Hydrogen is in emission from phase 0.75 to 0.00. The absorption lines of this star are generally weaker than in the M5 variables. The spectrum resembles No. 84 more than No. 42 or W Virginis. This is especially the case so far as the weakness of Fe II is concerned. On the strength of Fe II, the star would be classified as luminosity class III, but Ti II and Sr II are strong enough to call it Ib. Also weakened are Mg II λ 4481; Fe I λ 4260; and Sc II λ 4320.

c) Illustrations of the Spectra

Illustrations of the spectra are shown in Figures 4–7. Figures 4 and 5 show spectra with an original dispersion of 40 Å/mm taken very close to maximum light. Some standards are also shown. Particular points to note are: the early spectral type of TW Capricorni and No. 84; spectral type close to F0 for W Virginis and later than F5 for T Monocerotis; hydrogen emission for all variables except T Monocerotis, which has hydrogen lines that are too strong for its metallic-line spectrum; the weakness of Mg II λ 4481, in the population II cepheids; weakness of Fe II in TW Capricorni and No. 84; the strength of Ti II in the variables; weakness of Sr II in W Virginis.

Figure 6 shows spectra taken on the rising branch of the light-curve, along with standards at F0 II and F5 Ib. Of particular note are the hydrogen lines. The emission of W Virginis is much stronger than the other variables. For No. 42, H γ is almost filled in but shows very little emission. The weakness of Sr II λ 4077 in W Virginis is very marked. Fe II is distinctly weak in No. 84 and TW Capricorni but not in No. 42.

Figure 7 shows the high-dispersion plates. There are many points of interest. M5 No. 42 is closer to spectral type A7 than to F2. The structure of H δ shows broad wings, an emission component, and a displaced absorption core. The metallic lines of No. 42 are double. It can be seen that for Sr II λ 4077 the long component is more intense, while the nearby lines of Fe I have short components that are more intense. Number 84 at $\phi = 0.11$ has very broad lines, but they do not appear double. At $\phi = 0.34$ the strong lines of No. 84 are still broad, but many faint, sharp lines can be seen. The spectrum of T Monocerotis at maximum is very similar to γ Cygni, type F8 Ib. H δ is much too strong; it has a broader and deeper core than ν Aquilae, type F2 Ib, but lacks wings. Sr II λ 4077 is also much too strong.

d) Summary

These stars are more individualistic than the classical cepheids, and therefore groupings and correlations are more difficult to find; for example, in W Virginis Sr II is weak relative to Fe II, while in TW Capricorni the ratio of intensities is exactly the opposite. There is a big difference between the spectra of classical and population II cepheids. This is most apparent in the vicinity of maximum light, when the classical cepheids are

close to spectral type F6 with abnormally strong hydrogen absorption lines. The population II cepheids, on the other hand, have spectra of A5-F0 with either greatly weakened hydrogen lines or emission lines of hydrogen. The difference is so great for variables of period 15 days or more that a star can easily be separated into one of the two types using spectra of quite low dispersion. The weakness of Mg II λ 4481 is also striking in all the population II cepheids.

The general weakness of the hydrogen lines among the population II cepheids can be interpreted as meaning either that incipient emission is always present or that the metal abundance is very low and that the hydrogen lines are a true indicator of a lower temperature than that assigned by classification with the metallic lines. A brief summary of the observed spectral characteristics is shown in Table 3.

TABLE 3
SUMMARY OF SPECTRA OF POPULATION II CEPHEIDS

Period Interval (days)	Limits of Spectral Type	Hydrogen Emission	Double Lines	Period Interval (days)	Limits of Spectral Type	Hydrogen Emission	Double Lines
20-30	A5-G5	Present	Yes	10	F0-G0	No	?
15-20	A5-G0	Strong	Yes	1-5	A2-F8	No	?

This project was undertaken at the suggestion of Dr. W. Baade. I am grateful to Dr. J. L. Greenstein for his constant advice throughout the investigation. I have had valuable discussions with several members of the observatory staff, and with Drs. Kraft and Abt. The three Palomar plates of the variables were taken by Drs. Greenstein and Münch. The assistance at the telescope by Mr. A. Ratzlaff and Mr. A. Olmstead is also gratefully acknowledged.

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