SPECTROGRAPHIC OBSERVATIONS OF VISUAL DOUBLE STARS*

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ABSTRACT

The spectral types and estimated rotational velocities of the components of visual double stars are listed in Table 1. These quantities have been plotted against the photometric values of Δ mag., taken mostly from A. Wallenquist's catalogue. The results are consistent with the hypothesis that (*a*) the binaries have different ages, but the components of each binary have the same age; (*b*) in the younger systems both components lie on the "primordial" main sequence, which differs little from the sequence defined by the single stars of luminosity class V; (*c*) in systems of intermediate age the primaries are subgiants (luminosity class IV), with rotational velocities which, on the average, exceed those of the primaries of similar spectral types; and (*d*) in the oldest systems the primaries are subgiants of later spectral types and of smaller rotational velocities than their secondaries.

The data on visual double stars, contained in *Mount Wilson Contribution*, No. 511, have been presented in a form similar to that given by F. C. Leonard in 1923. The arrangement of the primary components, according to Δ mag. and Δ color is interpreted in terms of the ratios of the radii of the components.

The observational material discussed in this paper was obtained with the coudé spectrograph of the 100-inch reflector at Mount Wilson. Most of the spectrograms have a dispersion of 10 A/mm and cover the region λλ 3600–5000, but a few were taken with dispersions of 4.5 and 2.8 A/mm, respectively. The observing program was obtained from Aitken's (1933) catalogue, and preference was given to those physical systems which either could be resolved on the slit or might be expected to show double lines, if their separations were too small for resolution. Preference was also given to those systems whose brighter components were later than about A5 and whose components were not giants or supergiants. However, these rules were not followed rigorously, so that the material contains a mixture of binaries having different characteristics.

Spectral types for all observed components have been estimated from the plates by comparison with a series of MK standard spectra at the same dispersion, chosen from the list of Johnson and Morgan (1953). The series (A7, F0, F5, F8, G2, G5, G8, all main sequence), used in accordance with the precepts of the MKK atlas (Morgan, Keenan, and Kellman 1943), allowed us to estimate spectral types in any binary system, accurate to one or two subtypes. Luminosity effects are generally too subtle for reliable estimates, without having a suitable set of standards representing the several luminosity classes. The classes appearing in Table 1 are intended only as an indication of the probable luminosity of the object, as indicated in its spectrum. The magnitude differences have been taken directly from Wallenquist's catalogue (1954), with the exception of ADS 8202 (HD), 9375 (ADS), and 14279 (Johnson 1953). The rotational broadening of the spectral lines was estimated on all spectrograms, using an arbitrary scale of 0 to 10, where 10 represents the broadening in the brighter component of ADS 8257. A rough calibration of this scale indicates an equatorial velocity of rotation $V_{\rm rot} \sin i = 150$ km/sec for this star. Zero stands for lines of perfect sharpness, as in Procyon.

The data of Table 1 are represented in Figures 1 and 2. The co-ordinates of these figures are M_v and effective temperature. The luminosity branches III, IV, and V are plotted from Tables 1.3 and 1.5 by Keenan and Morgan, published in Hynek's *Astrophysics* (1951). In Figure 1, lines connect the same spectral types on the three branches

* The spectrograms used in this work were obtained by O. Struve as guest investigator at the Mount Wilson Observatory.

TABLE 1

SPECTRAL TYPE AND ROTATIONAL VELOCITIES OF DOUBLE-STAR COMPONENTS

ADS	NAME	SPECTRA: REW	SPECTRA: Adopted	ROTATION	Δm	TYPE
683*	65 PSC	g F0 g F0	A9 F2 III	9 9	0.03	I
903	77 Psc	d F5 d F4	F4 F6	3 0	0.81	III
3353*	....	d F2 d F3	....	5 0	0.11	III
4849	....	d F4 d F4	F5 F4	3 0	0.59	III
5166	20 Gem	d F6 d F6	F6 F4	2 6	0.62	IV
6483*	....	d F6	....	0	....	....
6977	....	d F5 d F6	F5 F3	0 1	0.70	II
6988	ι Cnc	g G6	G5 A5	0 15	2.57	IV
7187	....	d F3 d F4	F3 V F5 V	3 1	0.39	II
7307	....	d F3 d F2	F3 V F3 V	0 0	0.24	II
8119*	ξ UMa	d G0 d G0	....	0 0	0.48	II
8148*	ι Leo	d F4	....	3	2.85	....
8202	17 Cra	d F6 d F7	F8 G0	2 2	(0.08)	II
8257	....	....	F0 III F0 III–IV	10 3	1.35	III
8406	2 Com	d A8 d F2	F0 IV–V F0 IV–V	5 2	1.44	III
8505	....	d F4 d F5	F3 V F5 V	3 0	0.39	III
8519	....	d F2 d F2	F2 F3	10 5	0.09	III
8561	....	d F8 d G2	G5p G8p	0 0	0.59	II
8627*	....	d F6 d F1	....	0 8	0.03	....

* Not plotted in Figs. 1 and 2.

TABLE 1—*Continued*

ADS	Name	Spectra REW	Spectra Adopted	Rotation	Δm	Type
8630*........	γ Vir	d F0 d F0	F0 F0	3 1	0.02	II
8714........	....	....	F2p G0	6 0	0.76	III
8786........	....	d F5 d G0	F5 G0	0 0	0.47	II
8883........	....	....	K0 K2	0 0	0.30	II
8987*........	....	d A6n	A	10	....	....
9053........	....	d F7 d G1	F5 F8	5 1	0.65	III
9174*........	....	F0+A2	....	4	0.29	....
9375........	54 Hyd	d F1n d F9	F0 III G3	10 1	(1.9)	III
9413........	ξ Boo	d G5 d K5	G5 K5	0 0	2.16	II
9493........	....	F0 F0n	F1 F0	5 10	0.20	IV
9507........	....	d G5 d G5	G5 G8p	1 1	0.20	II
9535........	....	d G5 d G6	G5p G8	0 0	0.82	II
9580........	....	d F5	F5 G3	4 0	0.98	III
9617........	η CrB	d F9	G2 V G2 V	1 1	0.26	II
9728*........	....	d F6 d F6	....	1 1	0.09	....
9969........	49 Ser	d K0 d K1	K0 K0	0 0	0.09	II
10157........	ζ Her	d G0	(G0) (K0)	1 1	2.55	II
10993*........	95 Her	A1n g G3	....	10 1	0.13	....
11483........	....	d G0 d F8	G2 V G2 V	0 0	0.16	II
11639*........	ζ Lyr	d A9 A3n	....	3 15	1.38	....

TABLE 1—*Continued*

ADS	Name	Spectra REW	Spectra Adopted	Rotation	Δ_m	Type
12145*........	....	d G4 d K0	....	1 1	0.09	....
12169.........	....	d G3 d G5	G8 V G8 V	0 0	0.25	II
13868.........	....	d F6	F8 F8	0 0	0.79	II
14270.........	....	d G9 d G8	G8 K0	3 1	0.75	II
14279.........	γ Del	Sg K1 d F6	K2 IV F8 IV–V	1 1	(0.87)	II
14636.........	61 Cyg	d K6 d M0	(K5) (K7)	0 0	0.79	II
14773*........	δ Equ	d F5	F5 F5	0 0	0.1	II
15971.........	ζ Aqr	d F2 d F1	F2 F1	6 5	0.22	I
16417*........	....	d G1	....	1	....	....
16611*........	....	d F d G2	....	0 0	0.63	....
16979.........	107 Aqr	A5	F0 IV–V F0 V	8 4	0.97	III
17149.........	....	d G0 d G0	F8 G1	1 1	0.19	II

NOTES TO TABLE 1

683 Both components are giants. Not plotted in Figs. 1 and 2.
903 Secondary shows very sharp lines. This system will be treated more fully in a subsequent paper.
3353 South-preceding component is a spectroscopic binary. Not plotted in Figs. 1 and 2.
4849 Spectral type of primary may be uncertain.
5166 This system will be treated more fully in a subsequent paper.
6483 Separation too small to be resolved on spectrograph slit. Not plotted in Figs. 1 and 2.
6977 Primary is clearly later than secondary.
6988 Secondary has very broad, faint features.
7307 Sharp lines in both components.
8119 Both components are spectroscopic binaries. Not plotted in Figs. 1 and 2. Secondary shows broad emission in *H* and *K*.
8148 Not resolved on spectrograph slit. Not plotted in Figs. 1 and 2.
8202 Secondary has slightly sharper lines. Δm from *HD*.
8257 Primary has very broad lines. λ 4077 $\approx$ λ 4226. This system will be treated more fully in a subsequent paper.
8406 Primary has broader lines than secondary and shows stronger hydrogen. This system will be treated more fully in a subsequent paper.
8519 Both components show broad lines but the south-preceding component has very broad lines.
8561 Both components show fine cores in most of the lines, especially the primary. In the secondary, both hydrogen and iron lines are strong; *CN* is well developed at λ 3883.
8627 Both components are spectroscopic binaries. Not plotted in Figs. 1 and 2.

8630 The primary has slightly broader lines and may be bluer than the secondary. Not plotted in Figs. 1 and 2.
8714 *HD* remarks: "Spectrum appears to be composite. . . . The primary may be a close double." Our plates are too weak to study the peculiarities: hydrogen looks too strong; G band may be present. Note made at telescope: "m_v must be $\sim$ 8.5 and 9.2."
8786 High-velocity object, $v_r \sim 90$ km/sec (R. E. Wilson 1953). The secondary shows more lines, stronger G band, stronger $H\delta$, but equal or weaker $H\gamma$ than primary. This system will be treated more fully in a subsequent paper.
8883 Secondary shows strong *Al* I lines.
8987 Not resolved on spectrograph slit. Not plotted in Figs. 1 and 2.
9053 Secondary shows *H* and *K* in emission; suspected in primary.
9174 Just resolvable in seeing 4/10. Secondary may have wider lines. Both are early (A or F) showing *Ca* II H and $H\epsilon$ resolved. Not plotted in Figs. 1 and 2.
9375 Primary is very similar to ADS 8257A. If ADS 9375A is placed in the position of ADS 8257A, ADS 9375B would fall about 0.3 mag. below the IV sequence at $T_e \sim 5150$. Δm from ADS.
9413 Secondary is similar to 61 CygA (=ADS 14636A); *H* and *K* show sharp emission features, stronger than the continuum. Primary also shows *H* and *K* emission.
9493 Both components have broad lines; the secondary shows very broad lines. Spectral types uncertain.
9507 Both components show emission in *H* and *K*. Hydrogen is too strong in the secondary.
9535 Hydrogen is too weak in the primary.
9580 One plate (March 13, 1954) shows in the primary a combination of sharp and also rather broad lines. A later plate (May 17, 1954), taken for confirmation, does not show this effect so clearly. The secondary has very sharp lines and shows no obvious changes in the 2 months.
9617 Clearly resolved on a night of excellent seeing. The primary is approaching, the differential radial velocity being $\cong 10$ km/sec.
9728 The primary is a spectroscopic binary. Not plotted in Figs. 1 and 2.
9969 *H* and *K* are not in emission on our plates, which are rather weak in that region.
10157 Spectral types due to Struve and Ratcliffe (1954). R. E. Wilson (1953) gives $v_r = -69.9$ km/sec; possibly a high-velocity object.
10993 All lines in the primary are very broad; only hydrogen is obvious at 4.5 A/mm. Not plotted in Figs. 1 and 2.
11483 *H* and *K* may show double emission features in both components.
11639 A multiple system. The primary is a metallic-line star. Not plotted in Figs. 1 and 2.
12145 The secondary is a close visual double. Not plotted in Figs. 1 and 2.
12169 Johnson's colors (1953) show the primary to be slightly redder than the secondary; the spectra are very nearly similar.
13868 Johnson's colors (1953) are identical for both components. Spectra are very similar.
14270 A longer exposure may show *K* in emission.
14279 Δm from Johnson (1953). Primary is clearly not a dwarf; secondary may also be somewhat above the main sequence. Jenkins (1952) gives the parallax as $+0\rlap{.}''022 \pm 0\rlap{.}''005$; therefore, $m - M = -3.3$ mag., and $M_v = +1.0$ for the primary, according to Johnson's measure, $V_A = +4.27$.
14636 Spectral types from Johnson and Morgan (1953). R. E. Wilson (1953) gives $v_r = -64$ km/sec; possibly a high-velocity object.
14773 Wehlau (thesis, University of California, 1954) finds less than one subclass difference in spectrum. He quotes $\Delta m_v = 0.1$. Not plotted in Figs. 1 and 2.
15971 The secondary may be an unresolved astrometric binary. Lines in both components are very broad; in the secondary the weak lines appear to be shifted redward with respect to the strong lines. Not plotted in Figs. 1 and 2.
16417 Not resolved on spectrograph slit. Not plotted in Figs. 1 and 2.
16611 Secondary is a spectroscopic binary. Not plotted in Figs. 1 and 2.
16979 Both spectra appear similar, although hydrogen may be too strong in the primary.
17149 The secondary may be slightly later than G1.

shown. The points of Figure 5 are the locations of the primaries after the secondaries of the observed systems have been arbitrarily placed on the main sequence drawn in the diagram. In Figure 2 the primaries and secondaries have been connected, but in both figures only the primary has been plotted. The four different symbols correspond to the four categories in which the systems have been placed: *I*, spectrum of each component shows broad (*n*) lines; *II*, spectrum of each component shows sharp (*s*) lines; *III*, spectrum of primary shows markedly broader lines than secondary; *IV*, spectrum of secondary shows markedly broader lines than primary. The symbols in the diagrams are intended to show the relative line broadening of the two components, in each system. They contain less information than is given in Table 1; nevertheless, they bring out several interesting relations:

a) There is a striking tendency for the primaries to lie above the main sequence (luminosity class V). This tendency is especially pronounced among the hotter primaries, as shown in the accompanying table. This effect is identical with that discussed by H. L.

	No. of Primaries	
	Above V Line	Below V Line
Primaries hotter than 5700°....	17	4
Primaries cooler than 5700°....	7*	4

* Omitting one class II–III primary.

Johnson (1953). For comparison with our own results, we have replotted Johnson's data in Figure 3, showing the positions of the secondaries as they were arbitrarily placed in absolute magnitude upon the main sequence. ADS 5166 = 20 Gem and ADS 8257 have been plotted from photometric data on Johnson's system, which was supplied to us by D. L. Harris and by H. L. Johnson, respectively, at the McDonald Observatory. ADS

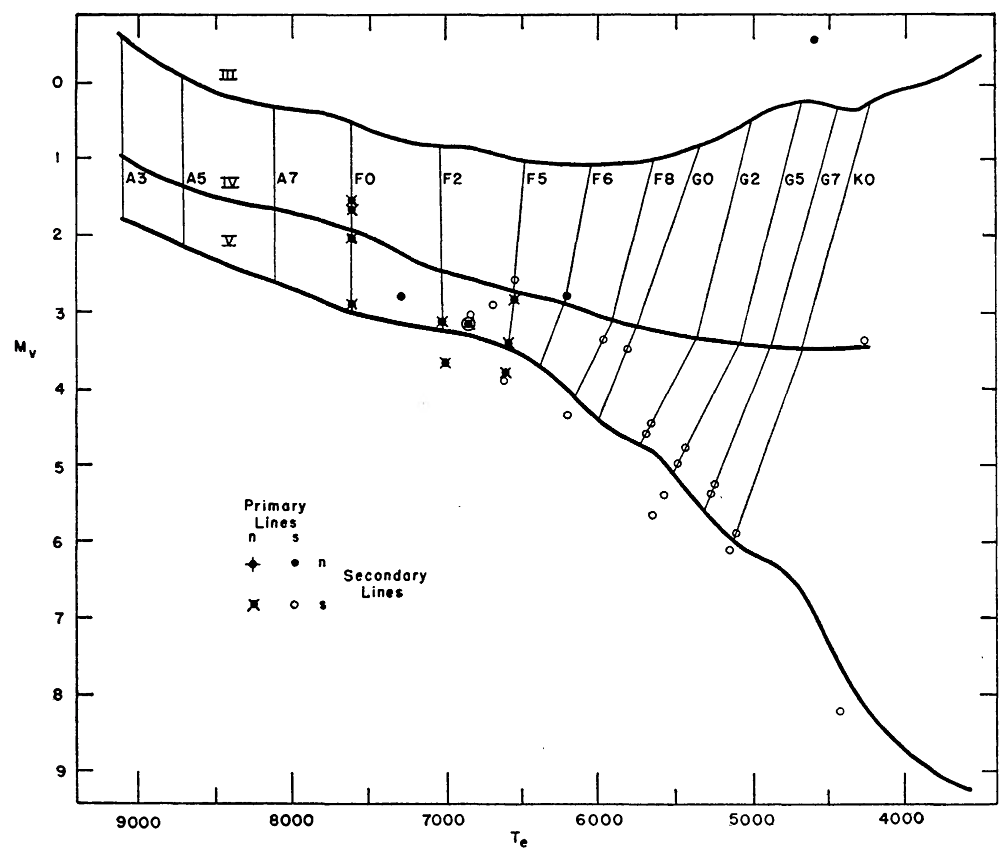

Fig. 1.—Effective temperatures derived from spectral types and luminosities of primary components of visual double stars.

5166 was also observed for us in six colors by G. E. Kron at the Lick Observatory. We have added to the diagram some systems published in the list by Johnson and Morgan (1953). The triple system is 36 UMa.

b) Only in two systems (ADS 903 and 4849) has the later component the broader lines. However, unpublished measures by H. L. Johnson show ADS 8257A to be redder than its secondary; ADS 8257 is a category *II* system. The lines in the spectrum of ADS 8257B are very similar to those of ADS 903A = 77 PscA, but the spectrum of ADS 8257A exhibits some of the broadest lines so far observed in this program. For this reason the spectral type F0 may be somewhat uncertain. With these two hypothetical exceptions (ADS 903 and 4849), the double-star components obey the general rule: the rotation, unless it is zero in both components, is larger in the one of earlier spectral type. This general rule has been known from previous investigations of single stars. But it is surprising that it should be obeyed so minutely by the double-star components. One might have expected that, since large rotations do occasionally occur among early F stars, an appreciable percentage of systems formed in a random manner out of single stars would show the narrower lines in the earlier components. But since our material is small, we cannot be certain that this peculiarity of the binaries is not due to chance or to a possible tendency of parallel orientation of the rotational axes in the two components of each system.

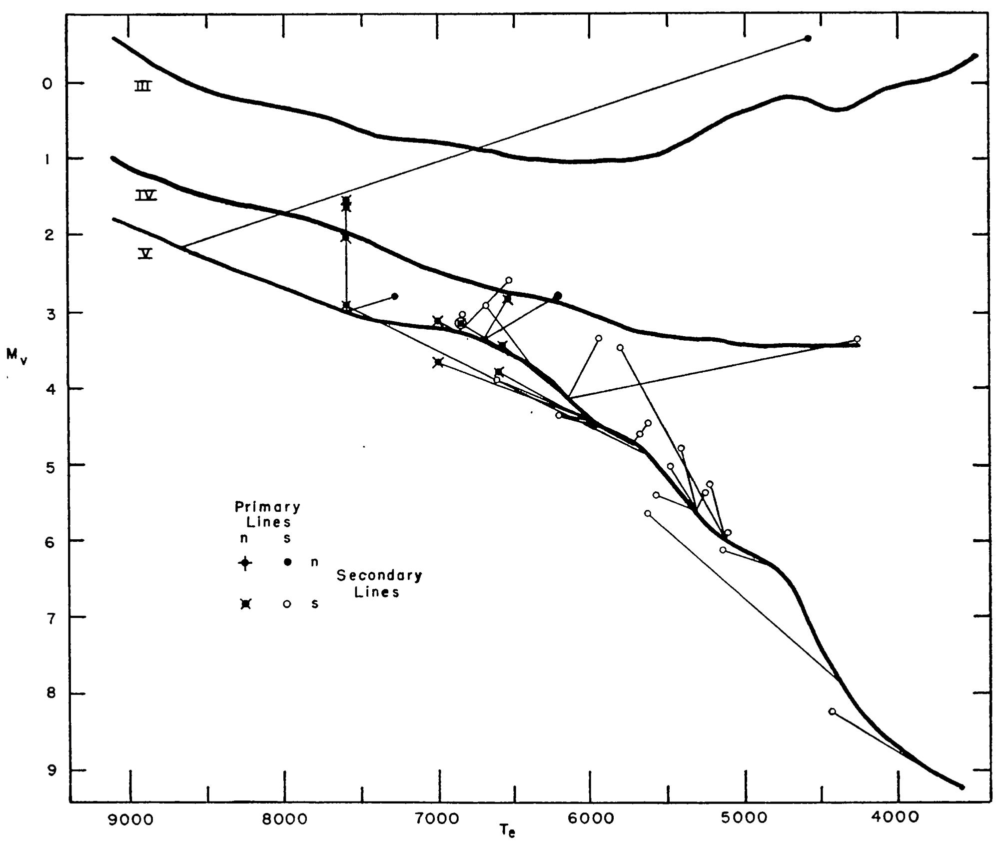

FIG. 2.—Relation between primary and secondary components in H-R diagram

c) Primaries whose temperatures are higher than 6500° K (or whose spectral types are earlier than the F7) very often have much broader lines than their secondaries. This is especially striking in the cases of ADS 8257, 8406, and 16979. ADS 9375 may also belong to this group. In these systems the primaries are subgiants (luminosity class about IV) with large rotational velocities. They are undoubtedly similar in character to the single subgiant F stars which J. L. Greenstein, G. H. Herbig, and A. Slettebak have found to possess large rotational velocities.

d) Two systems, ADS 5166 and 9493, have subgiant primaries which are redder than their secondaries and at the same time have narrower lines than the secondaries.

These results are compatible with the hypothesis that the locations of the primaries in the H-R diagram are the result of nuclear evolution, which proceeds more rapidly in the primaries than in the secondaries. According to A. Sandage (1954), M. Schwarzschild, I. Rabinowitz, and R. Härm (1953), Roy (1952), and others, unmixed stars may be expected to evolve along tracks which displace them above the main sequence and

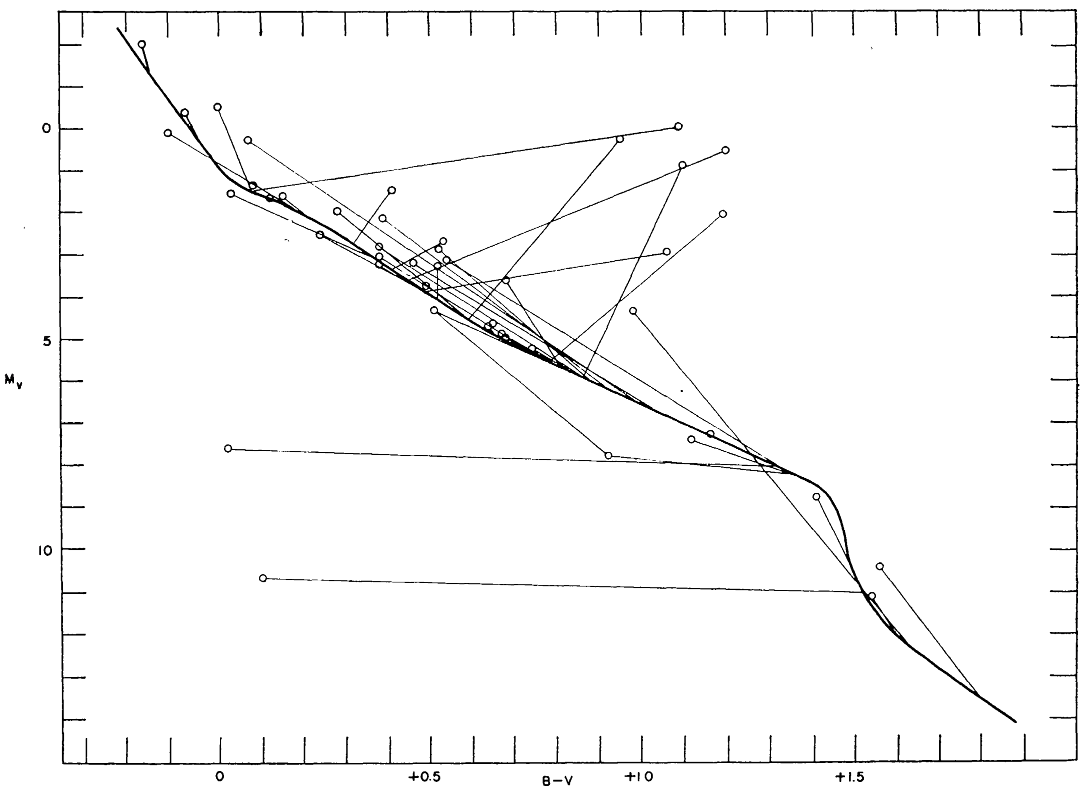

FIG. 3.—Color-magnitude diagram of visual double stars obtained mostly from H. L. Johnson's data

toward the right side of the diagram. Since the rate of evolution is sensitive to mass (or luminosity), it is reasonable to assume, as an approximation, that the secondaries have not had enough time to evolve appreciably off the main sequence. Hence we (and H. L. Johnson) have placed the less massive secondaries upon the main sequence (luminosity class V) in the diagrams. The primaries would then be located upon their respective evolutionary tracks appropriate to their masses, initial chemical compositions, and ages. The diagrams suggest that the binaries differ greatly in age: systems like ADS 7187 and 8505, both components of which are close to the main sequence, despite a considerable difference in luminosity, are relatively young, while systems like ADS 10157 (ζ Her), 5166 (20 Gem), 9493, and 6977 are old.

The observed rotational velocities of the subgiant primaries may be indicative of the law of preservation of the angular momenta of these stars. Consider, for example, three systems chosen to have roughly similar spectral types and rotations of the secondary components:

$$\text{ADS 8505}\begin{Bmatrix}\text{primary} & \text{F3 rot. 3}\\ \text{secondary} & \text{F5 rot. 0}\end{Bmatrix}\ \Delta m = 0.39\ ,$$

$$\text{ADS 4849}\begin{Bmatrix}\text{primary} & \text{F5 rot. 3}\\ \text{secondary} & \text{F4 rot. 0}\end{Bmatrix}\ \Delta m = 0.59\ ,$$

$$\text{ADS 6977}\begin{Bmatrix}\text{primary} & \text{F5 rot. 0}\\ \text{secondary} & \text{F3 rot. 1}\end{Bmatrix}\ \Delta m = 0.70\ .$$

We should regard the first as a young system, the second as of intermediate age, while the third is old. Similarly, if we compare

$$\text{ADS 8519}\begin{Bmatrix}\text{primary} & \text{F2 rot. 10}\\ \text{secondary} & \text{F3 rot. 5}\end{Bmatrix}\ \Delta m = 0.09$$

and

$$\text{ADS 5166}\begin{Bmatrix}\text{primary} & \text{F6 rot. 2}\\ \text{secondary} & \text{F4 rot. 4}\end{Bmatrix}\ \Delta m = 0.62\ ,$$

we should conclude that the youngest systems display the original distribution of equatorial axial rotations along the main sequence. Evolutionary changes of the primaries result in an increase in their radii and, consequently, in a diminution of the observed amount of rotational broadening. But this change is slower (at least among the earlier spectral types, A to F5) than the corresponding change in spectral type. Hence in such systems as ADS 8257, where the components have similar spectral types, the subgiant primary has much broader lines than its main-sequence secondary. The primary must have been, in its youth, an A-type star of very rapid rotation.

Since we now observe the effects of evolution in the appearance of the primary, similar but less pronounced effects should be present in the secondary, and we might not be justified in placing the secondary on the main sequence. That this objection is not entirely valid may be seen when it is remembered that the presently observed main sequence is defined by stars chosen without regard to probable age, but for the purpose of defining the sequences in the co-ordinates M_v and T_e. These stars may have a wide spread in ages; therefore, the present main sequence has a certain amount of evolution already affecting it. This tends to cancel any error we might make in placing the secondaries of visual binaries on the main sequence in order to study the evolutionary effects in the primaries.

A number of primaries are below the main sequence, underluminous for the dwarf spectral types. It is tempting to suggest that these may be very young systems, with both components lying on or near the primordial main sequence. However, it must be remembered that departures from the main sequence may have other causes. A few of the overluminous primaries may themselves be undetected doubles, or the companions of underluminous primaries may be double. Another cause which should not be overlooked is the accuracy of the data used in the construction of the main sequence. A more detailed standard spectral series may show a few irregularities in the assigned spectral types.

The hypothesis which we have advanced requires the evolutionary tracks of early-type stars to carry them predominantly toward the right side in the H-R diagram. If these tracks were predominantly along vertical lines, as Sandage (1954) has convincingly shown them to be for later-type stars like ζ HerA, it would be difficult to explain the frequent occurrence of appreciable rotations among the F-type subgiants.

In order to supplement our knowledge of the physical properties of the visual binary stars, we have constructed Figure 4, similar to one employed by F. C. Leonard (1923). For each suitable pair listed in *Mount Wilson Contribution*, No. 511 (Adams *et al.* 1935), we have plotted Δm_v when available from Wallenquist's catalogue (1954) against the difference in color, ΔC_s. The colors (C_s) were obtained from the Mount Wilson spectral types by means of the conversion by Seares and Joyner (1943). The points in Figure 4 are located according to the following visualization: if the pairs are plotted in a color-magnitude diagram and the components connected by a straight line, Figure 4 is obtained by transferring the line intact to the Δm, ΔC_s co-ordinates with the secondary component placed in the origin. The plotted point is then the position of the primary.

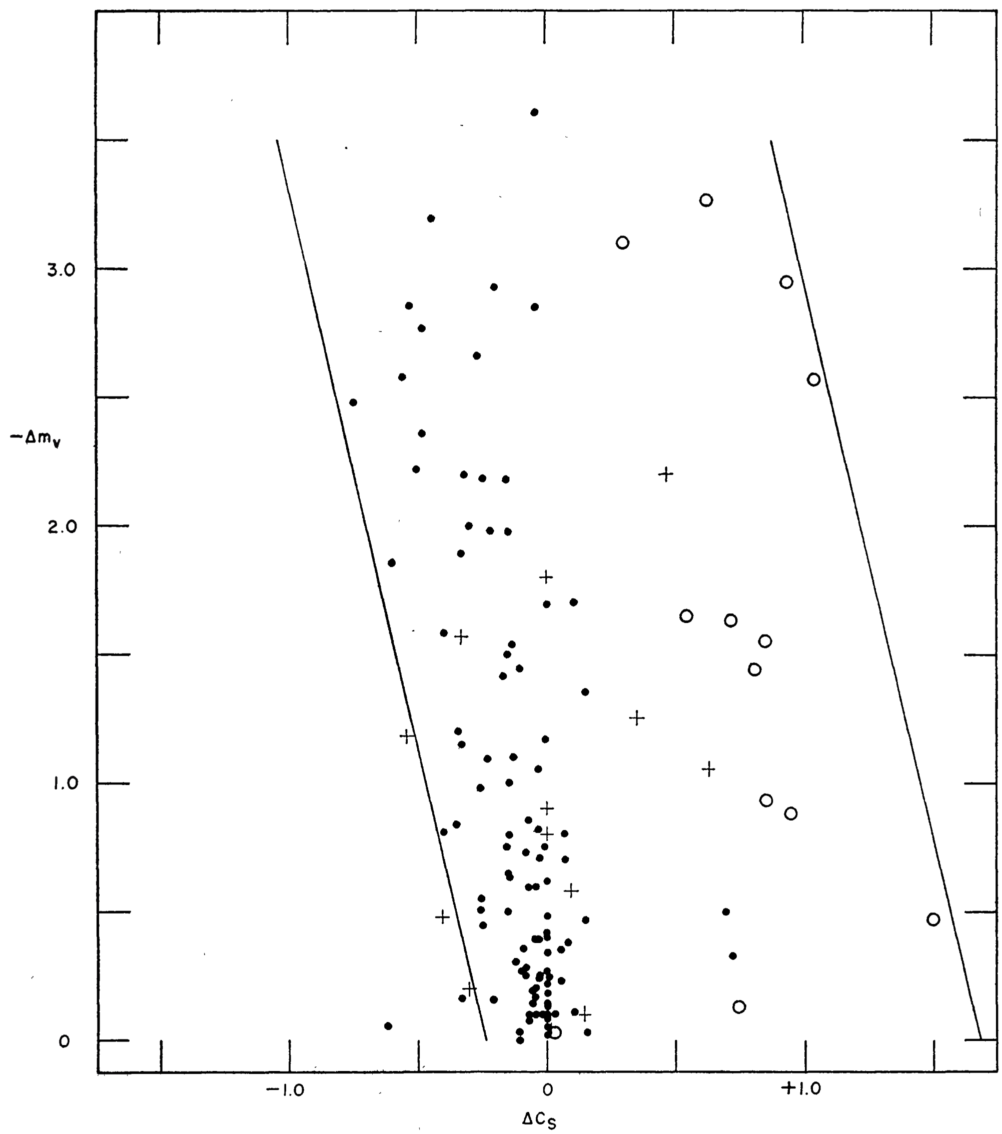

FIG. 4.—Plot of differences in magnitude and color for visual double stars

It is thus easy to understand the apparent separation in these co-ordinates of dwarf-dwarf systems (*filled circles*), giant-dwarf systems (*open circles*), and dwarf-giant systems (*triangles*). Giant-giant systems are vertical crosses.

If we assume that the stars radiate like black bodies, we may apply the formulae of Russell, Dugan, and Stewart (1938). Thus the following relation may be derived:

$$5 \log \frac{R^b}{R^f} = \Delta C \left(\frac{\lambda_2}{\lambda_1 - \lambda_2} \right) - \Delta M_{\lambda 1} + \beta ,$$

where

$$\beta = \frac{\lambda_1 \left(x^b_{\lambda 1} - x^f_{\lambda 1} \right) - \lambda_2 \left(x^b_{\lambda 2} - x^f_{\lambda 2} \right)}{(\lambda_1 - \lambda_2)} ,$$

and where b and f refer to the (visually) brighter and fainter components; R is the radius of the star; $\lambda_1 > \lambda_2$ are the effective wave lengths in centimeters at which the magnitudes are determined; ΔC is the color difference, bright *minus* faint; ΔM_{λ_1} is the absolute magnitude difference, bright *minus* faint, at λ_1; and

$$x = 2.5 \log_{10} \left(1 - 10^{-0.624/\lambda T} \right) ,$$

where T is the temperature in ° K. When the temperature difference between the components is small, β is small; any difference of the order of 1000° K may cause this term to be appreciable. If the components are hotter than approximately 10,000° K, β should be computed for differences less than 1,000° K.

Neglecting β and assuming wave lengths $\lambda_1 = 5500$ A and $\lambda_2 = 4400$ A (valid for Johnson's photometry and approximately for the International system), we find the coefficient of ΔC to be $+4.0$; thus ΔC is the most important quantity in determining the ratio of the radii of the components. The empirical limits drawn in Figure 4 represent approximately the slope of constant ratios of radii. These must be regarded as rough guides, since β may affect each system differently, depending upon the actual temperatures involved and may be either positive or negative.

By choosing a main-sequence secondary, one may find where the main sequence lies in Figure 4 by tracing out the locations of several different main-sequence primaries. Using the main sequence defined on the Mount Wilson system (Adams *et al.* 1935), we find that it has a mean slope slightly greater than $+4.0$ and that it passes through the origin of Figure 4. This mean line, however, passes on the left of the line one would draw as an average among all the main-sequence primaries shown in Figure 4. This indicates that most of the systems available for discussion show primaries whose radii are larger than they would be if they were lying on the main sequence. This is just the effect one would expect to find if these stars had undergone appreciable evolution, with consequent increase in radiating area. The evidence of Figure 4 supports the general relations already noted and is in agreement with the observation that many primaries are too luminous for their masses, as determined by Hertzsprung (1923), Strand (unpublished), and van de Kamp (1954).

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