THE MEASUREMENT OF RADIAL-VELOCITY DIFFERENCES BETWEEN THE COMPONENTS OF CLOSE VISUAL BINARY SYSTEMS

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Abstract. The value obtained for the difference in radial velocity between components of a visual binary that is unresolved on the spectrograph slit appears to depend, sometimes, on whether the measurement is made visually with a microscope or by means of an oscilloscopic setting device. This apparent dependence has been confirmed by measurement of artificially produced double-lined spectrograms, and disappears for line pairs separated by more than 1.5 or 2 times the half-widths of their components. The dependence arises from blending of the two line profiles. There is some evidence that the results obtained from visual measures are affected by the scale of the image being measured. For this reason, oscilloscope measures are probably to be preferred; although their errors are sometimes larger, they seem to be more consistent. Errors arising from this sort of blending are not sufficient to explain measures of relative radial velocity of the components of some visual binaries, that differ widely from the predictions made from the visual orbits.

1. Statement of the Problem

Although there are many reasons for making spectroscopic observations of visual double stars (Dommanget and Nys, 1967), spectroscopists have hitherto faced several difficulties when choosing an observing programme. These arise because the components of visual binaries with separations less than two or three seconds of arc are not resolved on the slitheads of most spectrographs. Even if the stars are resolved visually, it may not be possible to obtain uncontaminated spectra of each component, especially with a coudé spectrograph for which the line joining the two stars rotates with respect to the slit during an exposure. We use the term 'close visual pairs' to describe such pairs that are, at best, partially resolved. One must either choose to observe pairs in which the magnitude difference is so great that only one spectrum is visible – these are of limited interest – or to observe those in which the velocity difference is sometimes large enough for the two spectra to be resolved. In most pairs for which visual orbits are determined, the relative radial velocity is always too small for resolution of the spectra to be possible except with high-dispersion spectrographs. Until recently such spectrographs could be used only on the brightest stars, and the number of visual binaries for which relative radial velocities could be determined was very small. Improvements made to the coudé spectrograph at Victoria and its associated 48-in telescope during the last few years (Richardson, 1968) make it possible to obtain spectra of stars as faint as sixth magnitude at a dispersion of 2.4 Å/mm. One of the most important improvements is a mosaic of four six-inch gratings which permits the use of a collimator of longer focal length, and, therefore, the use of a wider slit. We can now resolve two approximately equal late-type spectra with relative Doppler

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shifts of less than 10 km/sec. When similar spectrographs are constructed for much larger telescopes much more work will be possible on close visual pairs.

Close visual pairs observed in the way just described can be regarded as spectroscopic binaries with very small values of K_1 and K_2. Most of their components have late-type spectra with fairly sharp lines. Even these sharp lines are wide compared with the separation between them, however. Thus errors may be introduced into the radial-velocity measurements by blending of the two profiles of a line pair (we call this *pair-blending* to distinguish it from the blending of neighbouring lines in the same spectrum). Pair-blending is well known in spectroscopic binaries, and has recently been investigated empirically by Petrie *et al.* (1967) and theoretically by Tatum (1968). In this paper we consider the effects of pair-blending on the sharp line profiles usually found in the spectra of visual binaries, and in particular the difference between oscilloscopic and visual measures of the separation of line pairs.

2. Observations and Measurements

This investigation was undertaken because of results obtained from the measurement of the relative velocity of the components of Σ 2173. These results led us to obtain and measure a number of artificially doubled spectra. We have also made use of spectrograms of the visual binary δ Equulei and discuss results recently obtained for A.D.S. 8189 (H.D. 100018).

Σ 2173: This system consists of two nearly identical G8 IV-V stars, of combined visual magnitude 5.3, with an orbital period of 46 yr. The expected maximum relative velocity of 12 km/sec. was reached in 1964–5 (Dommanget and Nys, 1967). West (1966) reported tentatively that the two spectra could be resolved on spectrograms of 8.9 Å/mm dispersion obtained in June, 1965. At his request we made observations from Victoria, but were unable to confirm his result until construction of the mosaic grating enabled us to obtain spectrograms of 2.4 Å/mm dispersion in May and June, 1968. We have measured the relative velocity of the two stars, and for this purpose it was more important to choose lines free of blending and pair-blending than to select carefully standard lines known to give good absolute velocities. The choice was easily made by inspecting the line profiles displayed by the oscilloscope before making any measures. A rather small number of fairly weak lines (width at half dept $\sim$45 microns) was chosen. When measured with the oscilloscope setting device, the spectrogram of 1968, June 4 yielded a value of

$$10.6 \pm 0.3 \text{ km/sec} \quad \text{(m.e.)}$$

for the relative radial velocity. The same lines on the same plate were measured visually on a Zeiss Abbé comparator and gave a relative radial velocity of

$$11.5 \pm 0.5 \text{ km/sec} \quad \text{(m.e.)}.$$

Although the difference is not formally significant, results from other spectrograms of this system show similar differences between the two methods of measurement. The difference is not a personal error, because each of us made independent visual measures and obtained closely similar results. The line separation on the photographic plate is about 70 μ, and the difference between the two measures is about 6 μ. As a result, the mass of the system is uncertain by about 25%. There is insufficient information on the plates to decide which measurement gives the correct result. The result from the oscilloscope device is closer to the predicted ephemeris.

δ Equulei: This system has a period of 5.7 yr and contains two closely similar late-type stars. Dr C. D. Scarfe has undertaken spectroscopic observations of the system, at 2.4 Å/mm dispersion, with a view to obtaining complete velocity curves for both components. He has kindly allowed us to use the spectrograms so far obtained. We chose one obtained on 1969, June 1 because it showed the smallest line separation of his best-exposed spectrograms, and measured 12 line pairs, chosen to be free of ordinary blending, both visually and oscilloscopically. We found the mean separation to be 88 μ (about 14 km/sec) by both methods. Most of the line pairs appeared well resolved, but some were only just resolved. The average width at half depth is in the neighbourhood of 60–70 μ.

A.D.S. 8189 (H.D. 100018): This is a triple system; the primary of the visual pair is a spectroscopic binary of period 7.4 days. The visual pair itself has a period of 86 yr. All three stars are of early *F* spectral type. The spectroscopic binary has been studied by Petrie and Laidler (1952). The visual orbit has been determined by Muller (1955) and Couteau (1965) and studied spectroscopically by Petrie and Batten (1969). The spectrum shows the lines of the spectra of all three stars. From the motion of the close spectroscopic pair, and the direct measures of the velocity of the visual secondary, the relative radial velocity of the two visual components can be inferred. It appears to be only about 50% of the amount predicted from the two visual orbits (Figure 1). The inferred radial-velocity difference cannot be reconciled with the visual orbit and the masses deduced for the spectroscopic binary within the system. On each spectrogram up to 10 line triplets were measured that contained lines of about 50 μ width (at half depth) separated by amounts ranging from 80–120 μ. All the spectrograms were measured visually. The possibility exists that the large difference between the expected and observed relative velocity of the visual components is a result of 'trio-blending'.

Artificial Double-Lined Spectra: In all the cases discussed above, we did not know what the true separations of the line pairs were. For this reason we made a series of artificial double-lined spectra, using two of the four gratings in the mosaic. The two gratings were deliberately set slightly out of adjustment, by varying amounts, so we could obtain two sky spectra slightly displaced, with respect to each other, along the direction of dispersion. Two comparison spectra were also obtained with the same displacement. We assumed that the separation of line pairs in the comparison spectrum could be

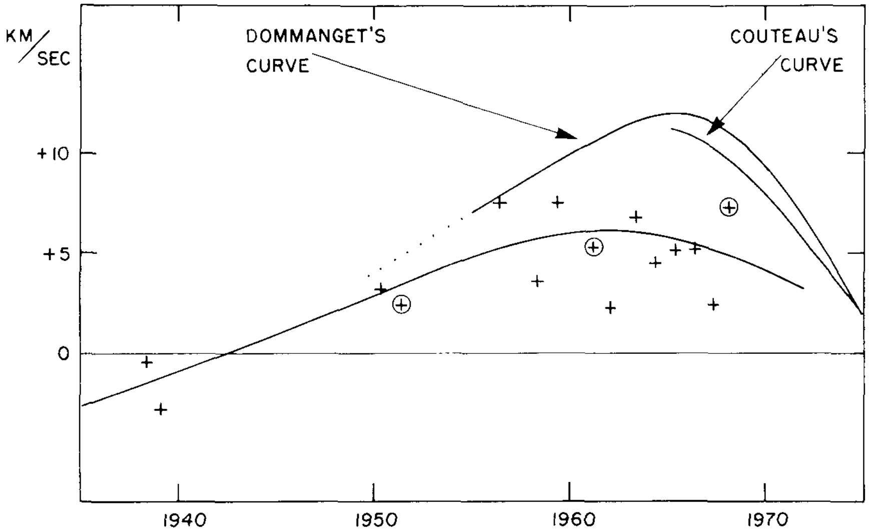

Fig. 1. Observed relative radial velocity of the visual components of H.D. 100018 compared with predictions from visual orbits. The three circled crosses have greatest weight.

measured without error. The ratio of the separation measured for pairs of stellar lines to that measured for pairs of comparison lines is a measure of the error (if any) in the measurements of stellar lines. We expected that the relevant parameter would be the separation of a pair of lines relative to the width at half depth (or half-width) of each of them, so we chose seven pairs of lines of different half-widths (ranging from 50–200 μ), being careful to choose lines free of ordinary blends.

The mean results from this series of plates are shown in Table I. The assumption that we could measure the separation of comparison lines without systematic error seems to be justified by the close agreement between the visual and oscilloscopic measures. In no case does the difference exceed one micron, which is well within the errors of measurement. The results of measuring the separations of stellar line pairs

TABLE I

Measures of artificial double lines

Comparison line separation			Stellar line separation			Stellar: comparison	
Visual	Oscilloscope	Difference (m.e.)	Visual	Oscilloscope	Difference (m.e.)	Visual	Oscilloscope
μ	μ	μ	μ	μ	μ		
252	253	-0.9 ± 0.5	248	247	$+1.2 \pm 2.2$	0.98	0.98
167	168	-0.9 ± 0.6	157	150	$+7.0 \pm 5.8$	0.94	0.93
105	104	$+0.7 \pm 0.6$	97	97	$+0.4 \pm 3.7$	0.92	0.92
90	91	-0.5 ± 0.4	84	81	$+3.0 \pm 1.7$	0.93	0.90
80	79	$+0.8 \pm 0.6$	74	68	$+5.7 \pm 1.8$	0.93	0.85
73	72	$+0.8 \pm 0.6$	64	59	$+5.2 \pm 3.0$	0.88	0.81

by the two methods differ much more, although only in one case is the difference formally significant. Oscilloscope measurements indicate that lines of a pair are rather closer together than would be deduced from ordinary visual measurements. The results for each individual line pair are plotted in Figure 2. The half-width of each line, which is used as the unit of measurement in Figure 2, was estimated on the oscilloscope screen. For lines of half-width less than 70 μ, the apparent total width measured visually agrees well with the estimated half-width. Wider lines are much wider than they appear visually.

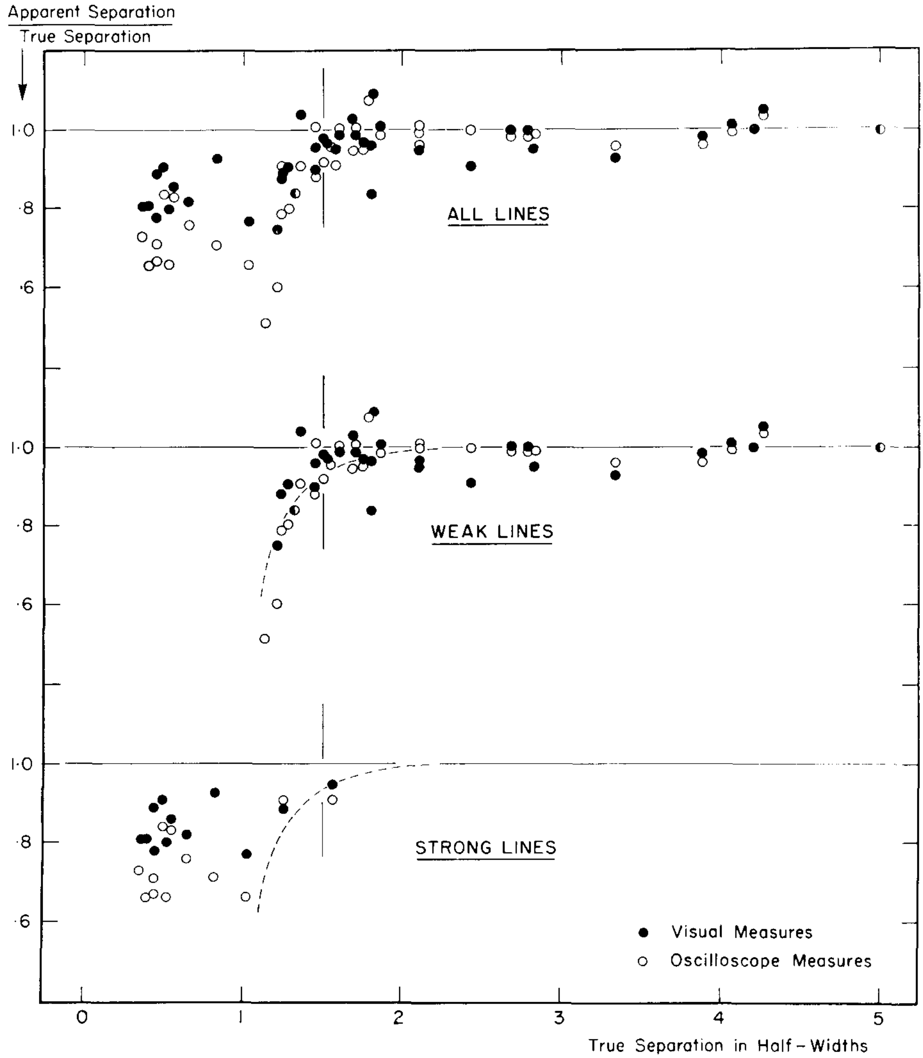

Fig. 2. Results of measurement of artificially double-lined spectrograms. Abscissae are the true separations expressed in terms of the line widths at half depth; ordinates are the observed separations of stellar line pairs divided by the mean separation of comparison line pairs on the same plate. The curved dotted line in the lower two sections shows the trend for weak lines.

Figure 2 shows that all line pairs are measured closer together than they really are if the separation is less than 1.5–2 times the half-widths of the components. At separations equal to or less than the half-width differences between the visual and oscilloscope measures appear. Figure 2 displays an interesting difference between the behaviour of the five weak lines (half-width 70 μ or less) and two strong lines (half-width about 150 μ). The strong lines show a smaller relative error at a given separation (expressed in units of half-width). The explanation may lie in differences in the shapes of the profiles. We could not measure the weak lines at as small relative separations as the strong lines, because pair-blending begins to affect the comparison lines at separations of 60 μ or less.

3. Discussion

The results show that either method of measurement gives approximately correct values when the separation of line pairs is greater than 1.5–2 times the half-widths of the component lines. At greater separations oscilloscope measures show a very slight tendency to give a more nearly correct result than do visual measures: they are certainly more precise. If there is any pair blending at all, the measured separation will be less than the true separation whatever the method of measurement. Below the critical separation, both methods of measurement give erroneous results. If the plate on which the comparison line-pairs have a separation of 73 μ were being used to determine the mass of a real stellar system, the total mass would be underestimated by 36% from the visual measures, and by 57% from the oscilloscope measures. The oscilloscope, presumably, measures the true positions of the minima in the combined absorption profile. We know these minima are pulled together by pair-blending. The eye appears to be able partially to compensate for this.

The line separation on the spectrogram of δ Equulei is large enough for no difference between the results of the two methods of measurement to be expected. This is also true of the spectrograms of Σ 2173. One factor has been changed between our work on Σ 2173 and the artificial double-lined plates. The Zeiss Abbe comparator has been converted from an ordinary visual microscope into a projection device. Measurements are now made while the measurer looks at a more highly magnified image of the spectrogram. We remeasured the 1968, June 4 plate of Σ 2173 using the new form of the Zeiss Abbe comparator, and found no difference from the earlier oscilloscope measures. This suggests that a measurer's visual judgment of separation of a line pair may be affected by the size of the image presented to him for inspection. We could not confirm this, however, from measures of the artificial double-lined plates. The situation is complicated by the appearance of a personal error between the two of us in visual measurement of the closest line pairs.

Although the visual measurements made in the course of this work happen to be nearer the true result than are the oscilloscope measures, the possibility of a personal error, and of scale effects, lead us to distrust them. The cause of the larger error in the oscilloscope measures is understood, and if theoretical line profiles can be assumed – in the present case probably instrumental profile – it can be calculated by the methods of

Tatum. Alternatively, our results can be used as a calibration if the line profiles in a spectrogram of a real double star are similar to the solar-line profiles on our spectrograms. It is gratifying to note the general similarity of our results to those obtained by Petrie *et al.* (1967) for much broader line profiles.

Finally we note that the results obtained from the artificial double-lined spectra cannot be used to explain the discrepancy between visual and spectroscopic observations of A.D.S. 8189. On all spectrograms measured of this system, the line separation exceeds 1.5 times the half-width. The combination of the two sorts of observation that is now increasingly becoming possible is likely to produce many difficulties of interpretation.

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Discussion

Rakos considers the results as surprising, and asks if a Grant measuring machine was used, the kind which performs very satisfactorily at Kitt Peak.

Batten: It is a modified Grant machine. We have to distinguish between the precision of a setting on a single line, which can be very great, and the accuracy of measuring the separation between two lines. In the latter case, with the Grant machine, one sets on the line profile minima, and these are known to be 'pulled in' from their true separation.

Strand thinks that the published trigonometric parallax of 0″.036 for Σ 2173 would not exclude the actual parallax to be half this value. Fracastoro suggests that the discrepancy between spectroscopic and visual results in ADS 8189 may indicate that double stars are not always examples of perfect two-body problems.

Batten thinks this is not important in the present case. The sort of effects hinted at are usually confined to the orbital plane, and are observed only in eclipsing binaries. Moreover, the stars discussed are of fairly late spectral type. It is also unlikely that the discordance can be ascribed to a strongly erroneous orbit inclination, as West suggested.

Finsen: I am always a little suspicious of radial velocities predicted by even fairly good visual orbits. It would be interesting to see whether an orbit based on both visual and spectroscopic observations would do serious violence to either of them.

Strand: Procyon is an example of close agreement between the data.

Heintz: The agreement and the prediction hinge on the elements e and ω, the only ones common to both sets in a combined solution (since the RV's usually are too scanty to help determine P and T). However in practice, as I experienced, almost every 'combined' case calls for a different evaluation.