(a) The semi-major axis a is shown by the integration to be a constant plus a small perturbing function composed of periodic terms. Hence a is stable.

(b) The eccentricity e_2 of the large orbit varies but slowly while more important changes take place in e_1 (for the inner orbit), and in the angle ϕ between the orbit planes. If ϕ is near 90° an instability results as e_1 periodically increases almost to unity. Since the variations are not purely in sine/cosine terms the averaged angle ϕ is slightly less, and the average eccentricity e_1 somewhat larger, than expected from a random distribution.

(c) The crucial parameter for the stability problem appears to be, not the ratio a_2/a_1 of the semi-major axes, but q_2/a_1, where q is the periastron distance. This value must exceed 3.5 for co-revolving systems and 2.75 for counter-revolving systems. But the observed limit (> 5) is still higher – a fact which may turn out to be cosmogonically significant.

Session 4. Photometric and Spectroscopic Data

THE PHOTOMETRY OF VISUAL BINARIES

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A substantial part of our understanding of the physical nature of stars rests upon observations of visual binaries. In order to secure a complete interpretation of a binary system we require these data: semi-major axis, parallax, period, magnitudes, colours, spectral types and velocities. It goes without saying that for very few systems are all these desiderata available, largely through technical difficulties of observing two images in close proximity to one another – and these difficulties are particularly serious in carrying out photometry. Nevertheless, the usefulness of photometry of binaries is so great that no effort should be spared in resolving the observational and technical problems.

Although the fundamental need for magnitudes is obvious in the case of establishing and improving the mass-luminosity relationship, there are other useful applications of photometry even among binaries of unknown period, orbital separation or parallax. For example, some visual binaries provide unique means of luminosity calibration through relating a star of unknown luminosity to another star having a well-established luminosity. In other instances, a binary's parallax can be inferred from the magnitudes when the system is too remote for the determination of a reliable astrometric parallax. Moreover, when the mass-ratio is not available from the astrometry, it can be inferred from the Δm, so that individual masses can be secured. A number of binary systems contain a variable star as one of the components – for example, Mira – so that here the roles of the visual binary observer and the photometrist are inseparable.

As a rule, photometrists are accustomed to achieving accuracies of 1 or 2 per cent and tend to turn away from photometric studies where such precision is beyond reach. It should be recognized, however, that the major source of error in mass-luminosity studies lies in the parallax which appears in the third power in the expression

$$M + m = \frac{a^3}{\pi^3 P^2}.$$

Consequently, magnitudes need not be determined to better than about 10 per cent for such purposes.

The combined magnitude and colours of a binary are easily secured by traditional photoelectric methods and here high accuracy is a simple matter. The crucial quantity is the Δm between the two components. When Δm is large ($>$ 3 mag) almost the entire uncertainty in it affects the magnitude of the faint component but not that of the brighter star, when the individual magnitudes are extracted from the combined magnitude.

To evaluate properly the existing Δm determinations and plan future programs it is profitable to review the techniques that have been devised and their limitations. It will be seen that there are three broad classes of technique, depending on the separation of the binary's components.

I. Separations larger than 10''. As a rule, these systems offer no difficulty to conventional photoelectric photometry. Consequently very reliable magnitudes and colours can be secured. Such systems, however, seldom are of interest to the orbit-computer since the periods are extremely long and an insignificant portion of the orbital arc has been observed. Examples of photometric catalogs of wide pairs are those of Eggen (1963, 1966), Johnson (1953) and Tolbert (1964). The photoelectric method can be extended to pairs somewhat closer than 10'' although guiding and centering difficulties and light-spillage from the excluded star require considerable care and attention. At Dyer Observatory we have measured, photoelectrically, two systems of about 6'' separation: Stein 2051 (Giclas 175-34) having Δm between 0 and 2 mag in U, B and V (Hardie and Heiser 1966); and FF Aql, having Δm's of about 5 mag in all three colours. For the first system the accuracy is

https://doi.org/10.1017/S0252921100150389 Published online by Cambridge University Press

normal, i.e. $\pm 0^{m}.02$ to $\pm 0^{m}.04$, while for the second it is considerably poorer, $\pm 0^{m}.2$. The most essential requirement for this type of photometry is to have a highly reliable drive system so that an image remains well centred in a small diaphragm (6″ diameter in the cases referred to) for several minutes. In addition, measures of light-spillage from a bright, single star close to the binary are needed; the image is placed out of the diaphragm at exactly the same distance as the binary separation and the proportional amount of spillage is measured. In typical cases it may amount to 5 per cent and since it is somewhat dependent on seeing quality, it should be done immediately before and after the measures on the binary are secured. We have even measured the Sirius system photoelectrically (Hardie 1971), in this instance through a 3″ diaphragm, dictated by the extreme Δm which places the B companion at about the same intensity level as the spillage from A.

It is probably safe to say, then, that conventional photoelectric photometry of high accuracy can be used for systems of any Δm provided the separation is greater than 10″, and if necessary it can be used down to about 6″ separation provided the Δm is no more than 3 or 4 mag. Whether there are a sufficient number of systems deserving this type of approach for reasons of precision or special astrophysical interest may be one of the matters the colloquium will consider.

II. Separations from 2″ to 10″. In this range, the grating-photographic method appears to be well suited. Strand (1969) has published a catalog of Δm's for almost 900 systems. The Δm is estimated by eye over a range that is restricted to $0^{m}.5$ or less by means of the grating. The materials used are photographs with multiple exposures taken primarily for astrometric purposes. Strand's analysis of his data shows it to be free of systematic errors when compared with photoelectric determination and the mean error of an individual measure is about $\pm 0^{m}.07$. The method is not useful for systems closer than about 3″.

Within this same range, visual techniques have also been used, for example by Pickering, Stebbins, Wallenquist, Hopmann and Miczaika (references may be found in Strand's paper) making use of either wedge or polarizing photometers. The work is not free of error, some of which originates in physiological properties of the eye, and the accuracies lie in the range from $0^{m}.1$ to $0^{m}.2$. There seems little doubt that the photographic technique, as practised at the U.S.N.O., is superior to the visual methods.

The new scanning photoelectric photometer technique introduced by Rakos (1965) and Franz (1966, 1970) offers still better accuracy and it now appears that this method may supplant all others mentioned thus far.

III. Separations less than 2''. There still remains the large number of systems whose proximity presents formidable obstacles to instrumental techniques and these are generally the systems of greatest interest to both the orbit computers and the astrophysicist. We will hear directly from Franz in this colloquium to what extent his technique will be applicable to these systems.

In this difficult range, Muller's (1948, 1951) pioneering work stands out; the instrument consists of his double-image micrometer and a polarizing element. The stellar images are split and the observer arranges their position in a rhombus; the polaroid is rotated until the primary image of one set is reduced to the same brightness as the secondary in the other set. The eye serves as a null indicator. Since the method is wasteful of light, very faint systems cannot be measured. Muller has determined Δm's for pairs as close as 0''.5 in this way and in certain instances he has used filters in order to secure colour indices. Worley (1969) and van Herk (1966) have used the same method for many close pairs and from an analysis of stars in common among these observers, Worley finds that the accidental and systematic errors are somewhat better than $0^{m}.06$, an extraordinary result considering the extreme difficulty of the technique and the demands in skill that it makes of the observer.

It should be apparent from this brief review of the principal photometric methods that the photometrist's chief contributions to the study of visual binaries can be twofold: the obtaining of Δm's and colour indices for those wider pairs that lie within the separation constraints of his equipment and the exploration of new sophisticated techniques which may open up avenues for observation of the closest pairs. In the first task he will need the advice and guidance of the visual binary specialist, especially in the form of catalogs of those wider pairs which for any reason need photometric study, whether this be for conventional magnitudes and colours, suspected variability, spectroscopic peculiarities or other matters of interest. In the second task, the photometrist may well call upon those who have so fruitfully wedded optical, radio and computer methodologies in recent years. We have witnessed the vigorous growth of modern optical physics, with applications such as Fourier and heterodyne spectroscopy, speckle and intensity interferometry to name only a few, so it is surely not too much to hope for a breakthrough in photometric techniques which will bring the closest pairs within reach.

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Discussion

Δm measurements in two colours for as close pairs as possible were rated most desirable, although the data on combined magnitudes of the fainter binaries (even at magnitude 8) frequently are also very weak.

Strand mentioned a systematic error he had found in van Herk's Δm values as compared with those of Muller, and Franz explained it as a difference depending upon the colour response of the system. Comparing Δm measurements, Franz demonstrates that there is a close agreement between his and Eggen's photoelectric results and a small systematic difference with Strand's eye estimates from plates. With the Lallemand camera at the Pic du Midi, Laques has measured Δm in UBV for about 40 doubles at separations between $1''$ and $2''$ and sometimes as close as $0\overset{''}{.}5$. He expected to switch to the Strömgren intermediate band system which he found easier to apply to his technique. His best results to date have errors of the order of $0\overset{m}{.}1$.

Franz has used the area scanner for UBV observations of 120 pairs. The smallest separations were about $1\overset{''}{.}7$, and the accuracy is of the order of $\pm 0\overset{m}{.}01$. In reply to a question by Hardie of whether a limitation to a lesser accuracy, say $0\overset{m}{.}1$, may lead to a larger output of results, Franz replied that the integration time is only 10 seconds while the on-line recording takes much longer, requiring three-fourths of the total time needed.

Abt emphasized that multi-colour photometry such as the Strömgren system or narrow bands (Hβ, Hγ) is preferable to spectra in providing the best data for the colour-luminosity diagram.