DEVELOPMENT OF PHOTOGRAPHIC TECHNIQUES FOR PHOTOMETRY AND POLARIMETRY OF FAINT STARS IN THE *R–IR* REGION

P. J. TREANOR, S.J.
Vatican Observatory, Vatican City State

Abstract. Photometric and Polarization measures of fainter stars ($m > 11$) are still very few, especially in the red to infra-red region. In order to exploit large Schmidt cameras to remedy this shortage, improved methods of photographic calibration are needed. This note reviews some of the problems associated with photographic calibration of direct images, and presents a progress report on the development of the ring polarimeter.

The study of the galactic interstellar medium at distances in excess of 1 kpc requires measures of magnitudes, reddening, extinction and polarisation of large numbers of stars fainter than the 10th photographic magnitude. Data of this kind are at present very scarce. It is evident, for example, from the review of polarisation measurements given by Serkowski (1973), that though the polarisation of several thousand stars is now known with considerable accuracy, nearly all these stars are brighter than $B = 10$. Moreover, measures at longer wavelengths, for example in the $R-IR$ photographic region are almost non-existent for fainter stars. The purpose of this note is to analyse the source of this imbalance, and to assess the possibilities of remedying it by the improvement of photographic methods of photometry and polarimetry.

1. Photographic Photometry

The advent of photographic techniques in astronomy at the end of the last century gave early promise of eliminating the large random and systematic errors of visual methods, and of extending photometric methods to fainter magnitudes. For example the early *Carte du Ciel* plates reached easily to $B = 12$ and frequently to much fainter limits. Modern large Schmidt telescopes obtain star images to $B = 19$ or fainter, so that one might hope for reasonably reliable photometry down to at least $B = 17$. However, even with the notable developments in stellar photometers, which ensure highly reproduceable plate measurements (with an internal consistency of three hundredths of a magnitude), the results of photographic photometry were very disappointing.

The non-linear and variable photometric characteristics of photographic plates, combined with the optical photometric errors of the astrographic refractors to create obstacles to accuracy which seemed almost insuperable.

After World War II the development of photomultipliers offered a solution to many of these difficulties. The linearity and the relatively low accidental errors of the photoelectric methods, combined with the possibility of immediate intercomparison of stars all over the sky, made possible the determination of accurate extinction correc-

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tions and the relation of the observed magnitudes to the network of stars which constitute the international UBV system. In polarimetry in particular, where the measures are largely differential, the development of multichannel polarimeters offered the possibility of measurements with an accuracy of the order of 0.001 mag. The development of photocathodes sensitive to wavelengths in the red and infra-red region made possible the extension of accurate wavelength dependence measurements to well beyond the limits of the photographic infra-red region. The break-through in accuracy thus achieved led to a concentration of research effort on this technique. The photoelectric method itself made an important contribution to improving the accuracy of photographic determinations, by providing numerous standard sequences which can be used to calibrate photographic plates and to determine field errors. The advantages of the photoelectric method were however so real that the last quarter of a century has seen a progressive lack of interest in photographic techniques of photometry, except for provisional extension of photoelectric studies to fainter magnitudes.

The photoelectric method itself is not without serious limitations. The method is relatively slow. Up to the end of 1966, UBV measures had been published for some 20000 stars, that is, less than one star per two sq deg, and of these the vast majority are brighter than $B = 10$. As a result it is very rare that an adequate photoelectric sequence, even to $B = 12$ is already available for the calibration of photographic plates. Outside the *UBV* wavelength range, the situation is very much worse. Photomultipliers sensitive to the longer wavelengths have considerably inferior magnitude limits, and have been much less generally used in extensive programmes. This situation does not seem likely to improve radically in the forseeable future. For the study of faint stars and in particular of the usually highly reddened stars at great distances near the galactic plane, and for intrinsically red stars, in statistically useful numbers for galactic survey work, the photoeletric method alone does not seem to offer much hope of providing a solution

It seem therefore appropriate to reconsider the possibilities of photographic methods in this context. In fact, much has happened in the field of photographic techniques since the advent of photoelectric photometry. Automatic measuring machinery, coupled with electronic data-processing methods, now makes it possible to measure up to 900 stellar images per hour. New emulsions, such as the Kodak 3aJ, and other emulsions of this family now under development for longer wavelengths, in virtue of their information storage capacity, reach fainter magnitude limits and promise higher accuracy than the emulsions hitherto available. Large Schmidt telescopes, in addition to their wide field coverage and faint limiting magnitudes, can be used over the whole of the photographic wavelength range. They are also, in principle, free from the troublesome systematic distance corrections, sometimes amounting to several tenths of a magnitude, typical of triplet and quadruplet photographic refractors, which also had the limitation of a narrow useful wavelength range. Schmidt telescopes do however have special difficulties, associated with the small size and low growth rate of their stellar images. This results, first, in an increase in the accidental error in magni-

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tude of the photometer measures of an individual image, and secondly in the difficulty of obtaining an exactly equal focus over the entire plate, which gives rise to a quasi-random distance correction. Methods of alleviating or even removing image-deformation effects have been suggested and tested. Some of these, such as the schraffier cassette and the Fabry lens method achieve this aim, but only at the sacrifice of magnitude limit and convenience of measurement. Others, such as the deliberate introduction of focussing or aberration errors, introduce systematic errors of their own.

A method at present under experiment by the writer aims at avoiding both these difficulties. It is based on an observational technique which is related to the ring-polarimeter technique. A plane parallel glass plate, slightly inclined to the optical axis of the telescope is placed just in front of the photographic plate. In contradistinction to the ring polarimeter, the angle of the plate is kept so small that the ring images produced have a diameter only two or three times that of the star images themselves. The available light is thus distributed in a symmetrical way over many more grains than in the direct images. Early saturation effects are thus avoided, and the ring image so obtained can be measured and reduced by normal iris diaphragm photometry. There is a small loss of limiting magnitude, but much less than in the schraffier cassette and Fabry lens methods.

The great shortage or absence of faint photoelectric standards, particularly outside the *UBV* region, create a special problem. The limitations of the objective-grating calibration method (Reddish, 1968) are well known. Recently a crossed calcite filter (Bruck *et al.*, 1969) has been used for calibration the random and systematic errors of this system (Pratt, 1968) are of the order of 0.1 mag. Other new methods have been suggested. Reddish (1968) has proposed the use of a mosaic objective prism which should have notable advantages over the objective grating. This would be a very costly expedient. The author (Treanor, 1969) has experimented with a split rotating conical

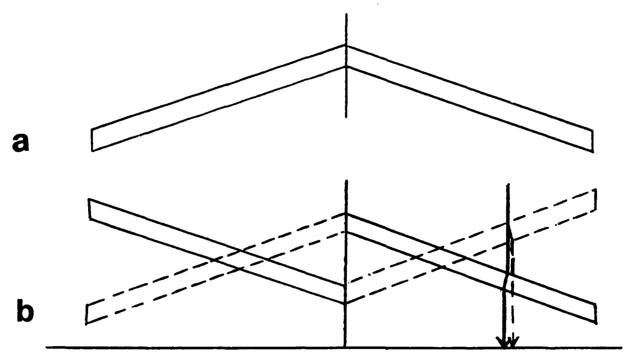

Fig. 1. *Double image formation by means of a split conical lens of zero power.* The circular conical lens shown at a is split through a diameter passing through the cone axis, and one semicircular section is reversed as shown in b. The pair are rotated during exposure about their common axis. Rays passing through the section P are always diverted towards the axis by a constant amount. Rays passing through Q are equally diverted in the opposite direction. The cone angle has been much exaggerated in the figure.

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lens of zero power (see Figure 1). One half of the split lens is inverted and covered by a neutral filter. The system produces double images with a known magnitude difference. However it is difficult to avoid image distortion with a system of this kind. The safest method seems still to be the half-filter method, for example in the 'reference' plate version described by Stock and Williams (1960), which is designed to eliminate most of the main systematic errors of successive exposures.

It should be emphasised that strict observance of photometric norms of exposure and processing are essential for this type of work. Apart from more obvious requirements, such as the exclusive use of photometrically good nights, and accurate control of the solutions, temperatures, and mode of plate agitation during processing, one should avoid working within 2 cm of 'original edges' of plates.

It is also advisable, with Schmidt telescopes, to restrict the measured field considerably, say to four sq deg, if greatest accuracy is sought. This applies perhaps even more strongly to lens astrographs, where one should work as far as possible reasonably near to the centre of symmetry of the distance correction which may or may not be the physical centre of the plate. (For the Vatican 4-lens Zeiss astrograph it is actually several cm distant from the plate centre.) Even in the absence of optical errors producing distance corrections, variations in the photographic emulsion lead to increasing errors the further one departs from the region of the calibrating sequence.

2. Photographic Polarimetry

The problems of photographic polarimetry are rather different from those of photographic photometry. Since one is here concerned with highly differential measures, the errors of the photographic process as such can be rendered small by a suitable choice of method. The main problem arises from the greater accuracy required for useful polarimetry. Even for the rather well polarised stars, to which photographic methods are applicable, on accuracy approaching 0.01 mag. in the amount of polarisation and 10° in position angle seems necessary for useful statistical work, although somewhat lower accuracy may be acceptable, for example in the search for very highly polarised stars. Existing methods, based on star image polarimetry use either successive exposures, between which a polaroid is rotated by a known angle (Pratt, 1968), or a calcite plate, simple or compound, which produces pairs of images corresponding to orthogonal polarisation aspects (Serkowski, 1960). The ring polarimeter method of the author is distinct from these that it uses a ringshaped image, the intensity of the circumference of which is modulated continuously by polarisation components at all angles (Treanor, 1968).

3. Errors in Calcite Plate Polarimetry

In this method a single plate gives pairs of images polarised at 90°. The measured intensity-difference between these image, expressed as a fraction of the unpolarised stellar magnitude, is related to the polarisation parameters by an equation of the form

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$$f_1 = 2p_0(\theta_1 - \phi)\,, \tag{1}$$

where p_0 is the fractional polarisation, ϕ the position angle of the polarisation, and θ is the position angle of the calcite axis plus an instrumental constant (Treanor, 1960). We need at least two plates with different values of θ_1 to determine p_0 and ϕ. Let us suppose the second observation is made (as is common practice) after rotating the analyser by 45°. We thus obtain

$$f_2 = 2\,p_0 \sin 2(\theta_1 - \phi)\,. \tag{2}$$

From (1) and (2) we obtain easily

$$p_0^2 = (f_1^2 + f_2^2)/8 \tag{3}$$

$$\tan 2(\theta_1 - \phi) = f_1/f_2\,. \tag{4}$$

Introducing the relation between polarisation in magnitudes and percent polarisation

$$p = 2.1717(p_0 + \frac{p_0^2}{3} + \ldots) \tag{5}$$

we obtain

$$p^2 = 0.54(f_1^2 + f_2^2)\,. \tag{6}$$

A mean magnitude error in a single iris reading corresponding to 0.03 mag. will produce an error in f of about 0.0425. The related error in f^2 is about 0.085, or $0.085\sqrt{2}$ in the sum, considered statistically. The corresponding error in p is therefore 0.033.

In practice the rotation of the analyser will be continued at intervals of 45° through 360°. These observations will reproduce three more pairs of equations, formally identical with (1) and (2), the observed values of f reflecting the effect of random and systematic errors. At best these additional measures can reduce the errors to 0.016. Some twenty plates (40 iris readings) will be needed to reach an accuracy of 0.01 in p. Similar considerations can be applied to the errors in ϕ determined from Equation (4).

Accidental errors of this kind apply also to all point image methods involving successive exposures with single images. In this case, the differences of sky transparency and the effect of successive exposures on the same plate will produce systematic errors which have to be determined by some form of comparison field. Systematic errors due to the deformation of the images in calcite plates also need careful study. These are not wholely eliminated in compound plates (Brand, 1971).

The ring polarimeter method goes some way, in principle, to diminishing these errors, though at considerable sacrifice of limiting magnitude. This last disadvantage is not too serious, since with a 38″ Schmidt, the method is still applicable to moderately reddened stars of $B = 13$. I note here some recent developments of this method, still in course of test, which aim to supply a deficiency in its original formulation. This development allows measurements of the amount of polarisation as well as of position angle to be made with rapidity from a microphtometric analysis of the rings. As will

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be recalled, the method as originally proposed, consisted in rotating a polaroid combined with a parallel-sided glass plate, slightly inclined to the axis of the telescope, just in front of the photographic plate. The star image was thus converted into a small ring, whose circumference has a varying photographic blackening. When this ring is rotated in front of a microphotometer slit, an approximately sinusoidal waveform is obtained, the phase of which is readily related to the position angle of polarisation, and the amplitude depends on the amount of polarisation. The problem not conveniently solved in the original exposition of the method was the interpretation of the microphotometer record in terms of the amount of polarisation. This has been solved as follows. One sector of the rotating polaroid and plate is covered with a filter of known transmission. The effect of this is to subtract from one sector of the star ring an intensity equivalent to a known magnitude step (say 0.2 mag.). A corresponding step-displacements occurs in the microphotometer record (see Figure 2). On the reasonable assumption of near linearity of the photographic characteristic curve over this small interval, the amount of polarisation can easily be calculated from the amplitude of the microphotometer record.

In order to test this method, it was found advisable to construct a specialised micro-

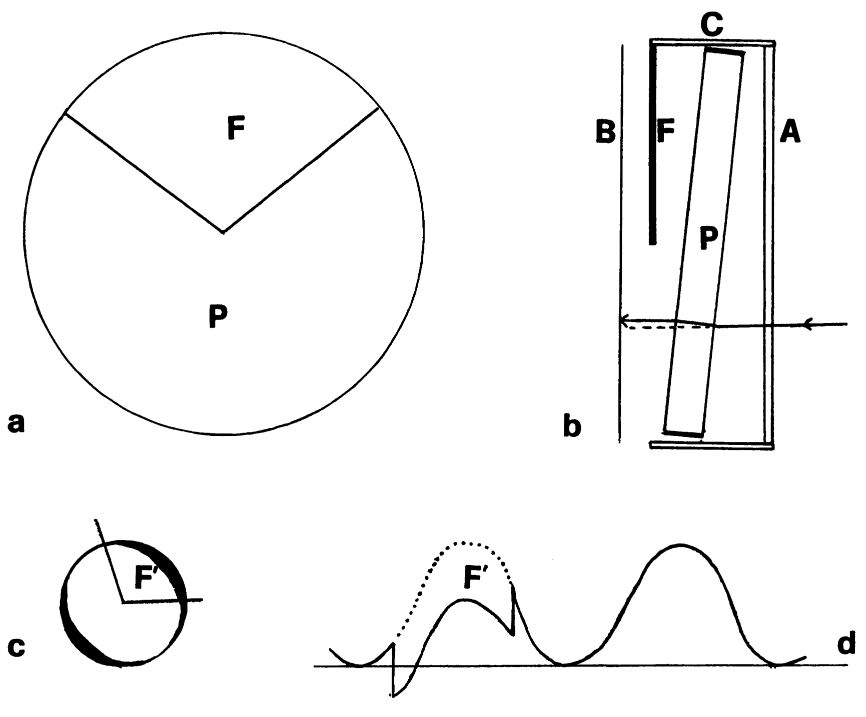

Fig. 2. *Calibration of ring polarimeter.* (a) Filter section F on inclined plate P. (b) Sectional view of polarimeter, showing polaroid analyser A, inclined plate P, Filter section F, rotating cell C and photographic plate B. (c) Idealised ring of highly polarised star showing the section F′ affected by the sector filter. (d) Idealised microphotometer tracing of ring circumference, showing the region F′ depressed by the sector filter of known transmission.

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photometer, the essential feature of which is that is that the optics are so designed that the rotation of the slit does not of itself produce any systematic effects on the illumination of the microphotometer photomultiplier. In this way it is possible to leave the plate stationary and to rotate the slit synchronously, rather than to rotate the plate, as was done in my earlier experiments. This is achieved by imaging the source of illumination of the plate on an end-window photomultiplier by means of a Fabry lens placed as nearly as possible in the plane of the rotating slit. This instrument is described in detail elsewhere (Treanor, 1973).

In the first tests, the calibrating step corresponded to about 0.08 mag. and took the form of a double 30° sector on opposite sides of the polaroid. Under these conditions, it was possible to allow the slit to cross the ring completely, so that the step appears on each repetition of the wave form. It is clearly identifiable on the registration (Figure 3). However, two defects are clearly present. First, the step is rather too small to define the scale well in relation to the noise level. Secondly, adjacency influence the height of the peak of the step, and also disturb the wave-form of the curve as a whole. By using a single sector, extending over 90° or more, and scanning with a slit terminating at the ring centre, and using a somewhat denser filter one may hope to eliminate the flaws of this initial experiment.

While it is still too early to predict the final accuracy obtainable by this method, one notes that the main source of random error is due to the rather prominent noise level due to grain emulsion, in this case 103aO. This can certainly be considerably reduced by using emulsions such as 3aJ. Other possible sources of error lie in the non-uniformity of the polaroid plate. This has recently been changed to accomodate a

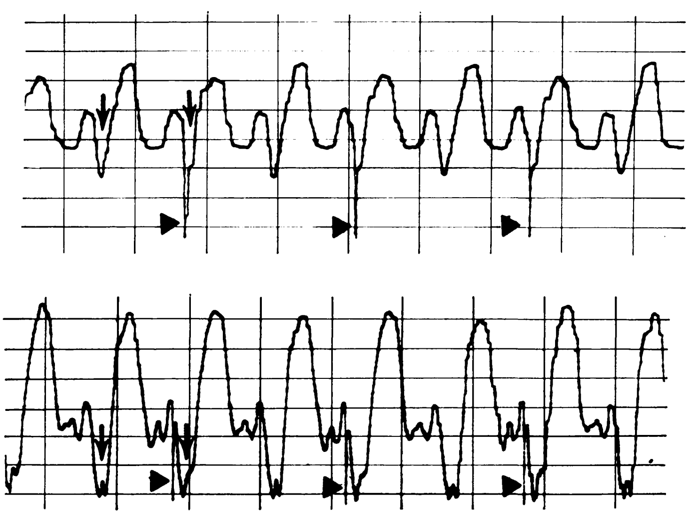

Fig. 3. *Registration of 2 highly polarised stars, showing calibration step.* The step corresponding to an intensity difference of 8 % was obtained using a double sectional filter of 30°, so that the step appears in each cycle of the registration, the single filter, which leaves alternate cycles unaltered, is preferable (see text). The filter step is indicated by a vertical arrow. The pulses which occur in alternate cycles, and which are indicated by the triangular spots are phase references signals.

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much larger field (about 8 sq deg). Now that a reference standard is available by means of the sector, these errors can be investigated quantitatively using a fine grained emulsion, in a field of stars with low polarisation. Since earlier experiments, even with 103aE, indicated that polarisations of 0.03 mag. were detectable easily from measures on four plates, the prospect of an ultimate accuracy of 0.01 mag. on finer grained plates does not seem to be excluded.

It must be acknowledged in conclusion that photographic methods remain difficult and of relatively low accuracy. The purpose of this note is to highlight the fact that for the photometric study of most of the Galaxy they are at present almost the only way of achieving adequate coverage. The difficulties of the past should not prejudice unduly our present assessment of their possibilities. With improved emulsions, and eventually with the development of practicable electronic area-scanning techniques capable of effectively replacing the photographic plates, the picture may change radically, and techniques which now struggle with the limitations of conventional photography may come into their own.

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