A fibre optic, four channel comparative photometer

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Abstract

Development of a four channel comparative photometer is described. Tests have shown that it is stable from night to night and is capable of working in very poor sky conditions. Even when the sky conditions are so poor that stars are barely visible light curves can still be obtained with an r.m.s. value of 0.0016 mag. provided that integrations times that are long compared with the transparency changes are possible.

1. Introduction

Increases in the stability and sensitivity of photomultiplier tubes and their ancilliary electronics over the last ten to twenty years have potentially allowed a major increase in the accuracy of photoelectric photometry. The fact that all sky, broad band photometry still has standard errors in the range of $0^{m}.01$ to $0^{m}.02$ and that comparative photometry, between stars separated by only ~ 1^{o} on the sky, seldom achieves standard errors below say $\pm 0\overset{m}{.}003$ suggests that the results are not as accurate as photon statistics alone would allow. Experience by the author, working at altitudes of 2,600 metres and 3,000 metres in the Spanish Sierra Nevada, one of the best sites in Europe, demonstrated that many nights which are visually perfectly photometric actually show slow, reversible changes in the extinction coefficient of a few percent. It is assumed that these changes are caused by variations in the aerosol size and concentration throughout the night but as the size of the effect is so small the effect cannot be detected visually even on bright, moonlit nights. The frustration of trying to produce accurate (millimagnitude) photometry on such nights, which contribute about one third of all nights in southern Europe, and on other nights when stars are visible, but the sky is spectroscopic rather than photometric led the author to consider the design of a multichannel comparative photometer.

Several groups, e.g. Piccioni et al. 1979, Grauer and Bond, 1981, have built two channel comparative photometers but the experience of the author with such a device at Herstmonceux indicated that two channels were not enough to render non photometric nights photometric. Typically although it was very clear that the comparison between the two channels showed variations it could not be ascertained whether all the variation was in one channel or whether both stars were variable. In addition it has become generally realised that for accurate photometry it is not sufficient to have only one comparison star, with perhaps a check star observed infrequently, but that at least two comparison stars are needed (unless one comparison star can be guaranteed stable at the millimag. level) and that equal amounts of time should be spent on all three stars. Thus the idea of a four channel, comparative photometer was born. The fourth channel was considered necessary to be used either to monitor sky brightness changes in bright sites or to allow a fourth star to be observed as an additional comparison on dark sites.

Below we describe two prototypes which have been built and the results that have been achieved with them. Both prototypes are (potentially) four channel devices and are known colloquially as four star photometers.

2. The first four star photometer

This first prototype was built in the years 1977/78 and used fibre optic bundles to take the light from the focal plane to a single photomultiplier tube. The use of a single detector was considered essential at this stage as it was not known how stable the relative sensitivities of different photomultiplier tube/HT unit/preamplifier discriminator combinations would be.

2.1 Description of the Photometer

The photometer consists of the following parts: 1) a focal plane device which allows apertures, Fabry lenses and fibre optics to be centred on either four stars or three stars plus one sky channel; 2) four 2 mm diameter fibre optic bundles taking the light from the focal plane to 3) a chopper box. This uses a rotating perforated disc to allow sequential interrogation of each of the four fibre inputs. A four into one fibre optic integrator allows each channel of input to be led to a common position after which a system of Fabry lenses and filters leads to the photomultiplier tube; 4) the detector, a single 52mm diameter EMI 9863/350QB photomultiplier tube; 5) a microprocessor which does all photon counting and on-line reduction. Each part is described in greater detail below.

2.2 The focal plane

A rectangular coordinate system (as opposed to an r, θ system) is an obvious choice for four objects in the focal plane. Four X,Y arms are provided, one on each side of a square (Figures 1 to 3). At their innermost ends they are provided with an aperture to be centred upon each area of sky plus star. These apertures are easily changed and three sizes are available on the current prototype giving fields of view on the 76cm Steavenson telescope of 1 arc min., 45 arc secs. and 32 arc secs. Underneath each aperture is a Fabry lens/prism assembly. This turns the light path through 90° in such a way that the light is deflected towards the outer end of each arm and produces a 1.7mm image of the primary mirror on the end of the fibre optic bundle. Each lens/prism/fibre optic bundle assembly is mounted on a motion block on each arm in such a way that the whole assembly can be moved outwards leaving the apertures clear to allow accurate centring of each object in its respective aperture. This is done with the aid of a travelling microscope permanently mounted on X Y slides positioned above those which carry the four arms.

In use the position of the four apertures is calculated beforehand from a knowledge of the stellar co-ordinates and the scale in the focal plane. All four lens/prism assemblies are retracted and the telescope moved until one star is exactly centred in its aperture. The other three arms are then adjusted until the other objects are centred in their respective apertures. The lens/prism assemblies are then returned to their inner positions which results in the light being deflected down the fibre optic bundles.

Because of the potential for changes in transmission efficiencies which could result from the fibre optics moving or drooping as the telescope moves it was decided that a calibration must be carried out, the equivalent of "flat fielding" with contemporary detectors, so that the signal in each of the four channels could be normalised. Therefore once the objects have been centred and the light deflected into the fibre bundles the calibration is carried out. This is simply done by illuminating a screen at the end of the telescope or viewing an illuminated area on the inside of the dome. Photons are counted, typically for one minute and the counts in the four channels used to normalise all channels for all further observations until such time as the procedure is repeated. The signals are then carried by the fibre optic to the chopper box.

2.3 The Chopper box

The four incoming fibre bundles, each with an active diameter of 2mm are plugged into the front of the chopper unit (See figure 4). The light which emerges from each bundle does so with an angle of approximately one radian. Each diverging cone of light is collected by a 3mm diameter fibre bundle which is one arm of a 4 into one fibre optic integrator which lead to a common 6mm diameter output. The distance between the 2mm diameter input and the 3mm diameter collector is slightly less than 1mm and it is within this gap that the chopper works.

The chopper is a rotating disc with an 85^{o} cut out slot. It also contains on one radius a single hole and on a different radius 4 holes. These in combination with opto switches index the position of the chopper both as to how many revolutions have occurred and as to which channel is being measured. Chopper speed is 25 rotations in 6 seconds. This curious rotational velocity was a result of not wanting to chop too quickly and perhaps experiencing scintillation effects, not wanting to use any simple subharmonic of 50 Hz which is the electrical mains frequency throughout Europe, and expediency with regards to the motors available. No claims are made that this chopping frequency is optimised but in practice it appears satisfactory.

The light which emerges from the 6mm diameter common end of the 4 into 1 fibre optic integrator does so with an angle of approximately one radian. In order to produce a scrambled image on the photocathode and to provide a more nearly parallel beam in which narrow band filters can be used a Fabry lens system is used to collect the light from this common end. This consists of two pairs of f/0.8 lenses, each consisting of two plano convex lenses, convex face to convex face. The first lens pair images the common end onto the second lens pair while the second lens pair images the pupil created by the first lens pair onto the photocathode. Between these two lens pairs is an interchangeable filter wheel with positions for six filters.

The photomultiplier tube, an EMI 9863/350QB, is contained in an air cooled Products for Research cold box and the Princeton Applied Research preamplifier/discriminator unit is bolted to the outside of the coldbox.

2.4 The Microprocessor and Peripherals

The microprocessor used is a Motorola 6800 unit in an Exorciser. The program is loaded from a floppy disc in an Exordisc unit. Input and output is via a Decwriter and a four-pen chart recorder provides a real time, visual indication of what is happening.

The ~1 volt pulses from the preamplifier/discriminator unit are first converted to TTL pulses and are then assigned to four registers controlled by pulses from the position opto switches on the chopper. The length of time for which each integration is carried out is controlled by software input from the Decwriter. At the end of each integration time, six seconds, ie. 25 rotations of the chopper, being the shortest time possible, the Decwriter prints out the following information. 1) Raw counts minus dark current for each of the four channels and the U.T. for the midtime of the integration. 2) The calibrated counts minus sky counts if a channel looking at only sky was used. 3) These counts converted into apparent magnitude using the mean photon arrival rate. 4) The magnitudes corrected by the secant of the zenith distance multiplied by an average extinction coefficient for whatever filter is being used. 5) The magnitude differences between the first channel and the other three (or two if a sky channel was used) and the sec Z for the middle of the integration. The chart recorder displays the sec Z corrected magnitude in channel one, which is essentially a record of the sky transparency conditions plus any real changes, and either the two magnitude differences if a sky channel was used or the three other magnitudes if no sky channel was used. These are updated every six seconds for the chart recorder only.

2.5 Results

Below we will demonstrate three aspects of the machine's performance. These are 1) its ability to work through clouds, 2) its ability to compare results taken on different nights and 3) its performance under good sky conditions.

Figure 5 shows a 5 hour run on the eclipsing Wolf Rayet star CQ Cephei. The V magnitude of this star is about 9.2 mag. The results were obtained through a narrow, F.W.H.M. 100 Å, filter centred on λ5300 and through up to 1.3mag. of extinction resulting in an equivalent magnitude through a broad band filter of ~11.5 - 12.5. The observations were obtained on the 76cm Steavenson telescope in the Spanish Sierra Nevada. It will be seen that for the first ~4 hours of the observation the sky transparency was continuously variable due to a combination of cirrus and stratus clouds. No moon was visible. On the same scale below the plot of CQ Cep. we show the mean magnitude difference CQ Cep - HD214259 (AO, m_V = 8.7) used by Hiltner (1950) as a comparison star and CQ Cep - HD214220(AO, m_V = 8.8). Finally at the bottom of figure five we show this same mean magnitude difference again but this time with the vertical scale amplified by X10 in order to show details. The eclipse is clearly visible and the time of the centre can be determined to within a few minutes. In addition detailed analyses of these data in comparison with other data (Walker et al. 1983) showed that structure in the light curve of $0^m.005$ was detectable. We believe that this demonstrates the ability of the machine to produce results on fairly faint stars (~12m_V) on a relatively small telescope (76cm with 25% blocking by baffles to allow a 1^o field of view) on nights with over one magnitude of variable cloud cover.

A second demonstration of the machine's ability in cloud is contained in Figure 6. Here we show the comparison between η Cyg (m_B 4.9) and HDE226868 (m_B 9.6, the optical counterpart of Cygnus X-1). This night had been cloudy, cleared and then clouded completely to the extent that at the end of the one hour run the sky was six magnitudes down. At the top of figure 6 we show the delta-magnitude η Cyg - HDE226868. This changed by ~0.05 mag. while the signal from both stars fell by about 6 mags. We are not claiming that the machine will work properly through an intensity change of ~250:1. Any errors in the respective calibrations of the various channels would be amplified by this amount and with small telescopes the stars are invisible so that guiding is impossible. This example is presented only to demonstrate the potential inherent in the method.

The second aspect of the behaviour to be shown is the ability to compare results obtained on different nights and with different sky conditions. It is in effect a test of the flat fielding procedure. Figure 7 shows the blue magnitudes of HDE226868 relative to η Cyg on 12 nights during one lunation during October 1981. The nights varied from good to cloudy with the moon being present at all phases from full to new. The data have been folded with the 5.599824 day period and are shown compared with a mean curve obtained over the previous eight years (Walker and Rolland, 1978). It has long been known that the light curve of this optical counterpart of Cygnus X-1 is variable with time and therefore the different amplitude of the two curves is not significant. Although the dashed line connecting the new observations is made to fit the data it would appear that scatter round it is small and about 0.002 mag.

Finally we wish to show the performance of the instrument under good sky conditions. In Figure 8 we show results on 3 Hyades group stars, 89,91 and 92 Tauri. 92 Tau was found to be variable. In the upper part of figure 8 we show the signal for 92 Tau without any Sec Z correction. Below we show the magnitude differences between 92 Tau - 89 Tau and 92 Tau - 91 Tau. The variation of 0.07 mag in 2 hours is clearly visible in both plots.

3. The Second Four Star Photometer

Following the experience with the original device described above it was decided to see whether a four channel system could be built using four separate photomultiplier tubes and their ancilliary electronics. The potential advantage of such a device is that there are no chopping losses or transmission losses in the rather complex optical train of the first prototype. Thus the overall efficiency of such a system should exceed that of four telescopes of equal size to the telescope in use, each equipped with a normal photometer. (Note that compared with a single telescope and conventional photometer which spends significant amounts of time moving from star to star that overall efficiencies are increased by much more than the factor four.) Potential disadvantages of such a device include 1) changes in relative sensitivities of the four detector systems either with time or angle with respect to the earth's gravitational and/or magnetic field; 2) differential transmission changes of the fibre optics as they droop by differing amounts as the telescope moves. Note that in the first prototype after initially moving the arms to centre the apertures on the stars, the transmission of the four light paths was calibrated and the fibre bundles, which were stiffened, were not moved thereafter. Remembering that the ultimate aim of comparative photometry is to work at or below (when photon statistics allow) the one millimag., i.e. 0.1%, level and that typically the relative sensitivities of PMT systems and fibre optics are not known to this level it was necessary to check the stability of the various components.

3.1

Experiments were performed to measure the change in transmission of fibres as they were bent. These will not be reported in great detail here but as the results might be of some wider interest some of the details are described. Three types of fibre were tested. Two of them were samples available and were used merely because they were available, not because they were ideal choices.

These were ~60 cms (2 feet) of 600 μ diameter plastic clad quartz, ~20 metres (60 feet) of ruggedized, plastic clad quartz, 250 μ diameter, both from Quartz et Silice, France, and a 2mm diameter bundle of 100μ diameter quartz fibres, 1.8m (6 feet long) properly enclosed and with the ends terminated.

The ends of the first two samples were roughly optically polished and terminated before the experiment. Two types of experiment were performed. In the first the input end of the fibre was placed ~4 cms away from a 15 mm diameter Beta light source, the fibre end and the Beta light source being rigidly mechanically mounted in a light-tight box. The output end of the fibre was rigidly mounted into the front of a cold box containing a 52mm diameter photon counting tube and connected to standard photon counting electronics. No attempt was made to focus either the input or output end of the fibre. Tests typically consisted of performing several tens of individual 1-100 second integrations, bending the fibre and repeating the counts. By making many measurements before and after the movement we could ensure that the results were due solely to photon statistics and not due to drift in either the light source or tube sensitivity. The longest experiments suggest that for all reasonable movements of the fibre no change greater than 10^{-4}, ie equivalent to ~0.0001 mag., occurred. Shorter experiments put upper limits on changes of $\sim 10^{-3}$. Bending the fibre to near its mechanical limits could produce changes of > 1%.

The second set of tests involved putting a Fabry image on the input end of the fibre and then repeating the tests as above. The setting up of a stable mechanical system to allow an f/15 beam to produce a ´stellar´ image in front of the Fabry lens and for the lens to produce, for example, a 100 μ diameter Fabry image on the 250 μ diameter fibre was difficult. An incandescent bulb fed from a constant voltage transformer through a constant current supply, with stabilisation at about 0.1% proved inadequately stable and resort had to be made to Beta light sources once again. Temperature stabilisation of these to $\sim 1^{o}C$ was required. Eventually we were able to demonstrate that stabilities in the range 10^{-3} to 10^{-4} were obtainable and in fact all tests were consistent with there being zero change, ie below the sensitivity range of our tests. Therefore, laboratory tests, which mimicked as closely as we could real observations, suggested that when any of these three types of fibre are bent, by amounts which do not cause mechanical stress, no change occurs in the transmission which is greater than the equivalent of 0.001 to 0.0001 magnitude.

3.2

Following the tests on fibres a similar set of tests were carried out on a 3mm diameter x 2 metre long UV transmitting fluid light guide. Compared with fibre bundles these have ~ 40% higher efficiencies due to the lack of packing fraction losses. Tests on the input sensitivity were carried out with the image of a beta light source either on the end of the fluid light guide or ~6mm outside the end. f/ratios of f2, f5.5 and f11 were used although vignetting occurred for the two faster f/ ratios when the image was 6mm outside the end of the light guide. Figure 9 summarizes the results which were obtained by taking many repeated measures in each position to ensure that the results were limited only by photon statistics. No significant variations occurred except for the case of the f11 beam being focused on the end of the light guide, demonstrating, once again, the dangers of dirt on optical surface when small images are used.

The tests on variations in transmission with bending were of exactly the same type as carried out on the fibre optics. Despite the larger diameter of the fluid light guide, when compared with the individual fibres, it was still possible to obtain acceptable results by ensuring that the light guide was not able to bend to its mechanical limit. For slight curvatures, changes were in the range 0.001 - 0.0001 magnitude, i.e. not significant at the limit of the tests while near to the mechanical limit 1% changes were measured.

3.3

Additional tests were then kindly carried out for the author by French amateur astronomer, Claude Gregory, from his home observatory near Banon, South of France. He used a single channel photometer fed by a fluid light guide and attached to his 28cm telescope by an interface made by the author. The photometric standard star 27 Leo Minor, m_V = 5.878, B-V 0.15 was observed for approximately 3 hours up to meridian crossing. The star was observed at 15 to 20 minute intervals through a V filter. The ambient temperature was -10^{o}C. Figure 10 shows a histogram of the results. The only correction applied to the raw data was sec Z multiplied by the V extinction coefficient of 0.39.

The standard error of the mean of the ten measurements was ±0.0018 while the probable error of a single measurement was ±0.006. This adequately demonstrates the usefulness of the light guides when used under real observing conditions.

3.4

Having demonstrated the stability of the fibre optics and light guides it was necessary to ascertain the relative stability of different photomultiplier tubes as they are tilted relative to the earth's gravitational field. It is well known that tubes can change their sensitivity when reorientated relative to the earth's magnetic field and therefore each PMT was placed in a mu metal shield inside either a Products for Research or EMI Gencom cold box. Three PMTs only were available. All were 52mm diameter 14 stage tubes, two with S11 photocathodes and one with an S20 photocathode. The PMTs, their cold boxes and the ancilliary electronics were all allowed to stabilize for several days before the tests. For the tests the PMTs in their cold boxes and with their individual preamplifier/discriminators were placed on a rotating platform with its axis of rotation angled at ~45^{o} to the vertical. Each PMT was fed by a 2mm fibre optic bundle from a beta light source. The fibre optic bundles were supported so that no movement could occur. The PMTs were supported on the turntable in such a way that their longitudinal axes lay parallel to the surface of the table and the test consisted of monitoring the output of the tubes before and after a rotation of the turntable of ~90^{o}. One tube changed its sensitivity by ~0.5%, one by ~1.0% and the third by ~5%. The changes were reversible when the turntable was returned to its original position. Considerable examination and physical checks failed to show any reason why one tube should be so much worse than the other two. If these results are confirmed by further tests then this is clearly another cause of error in conventional photometers.

3.5

The second prototype therefore consisted of the original microprocessor controller/counter and ancilliary printers, chart recorders, etc.; the original four arm focal plane device and fibre optic bundles etc., and the three PMTs and their ancilliary electronics used for the tests above. The least stable PMT was used to monitor the sky signal. Lack of official English support for the device meant that the tests had to be undertaken with the aid of astronomers from Nice observatory in the South of France. A telescope was available for ~ 2 weeks over Easter 1985. Calibrations of the relative sensitivities of the three channels was carried out at ~ 30 minute intervals.

The weather was bad during the two-week observing run which was undertaken on the 40-cm 100-year-old coude refractor of the Nice Observatory. This is sited on the edge of the town, 300 metres above the sea. The lights of the town are bright enough on the site to allow fine newsprint to be read. For the tests we decided to observe the Delta Scuti star 20 Canum Venaticorum, as it was reputedly a low-amplitude ($0\overset{m}{.}02$ peak to peak) monoperiodic (2^h 55^m) variable. HR 5004 was used as a comparison star while the third channel monitored the sky brightness. A broad-band B filter was used. Results were obtained only on three nights. The longest observing run was that of the night 20/21 April 1985, when about four continuous hours of data were obtained. The sky conditions were very bad, with a hazy sky making stars away from the zenith invisible to the naked eye. Above the haze, bands of cirrus clouds passed continuously while below the observatory fog banks rolled in from the sea to partially obscure the town of Nice. The data for this night are shown in

Figure 11. The upper curve shows the apparent magnitude of the variable with a B-band extinction coefficient of $1\overset{m}{.}3$ (5 x the normal figure) removed. The erratic brightness changes, the passing bands of cirrus, and finally the clouding up of the night all can be seen. The lower curve shows the delta magnitudes between the two stars, the values having been obtained over 20-minute intervals at 10-minute spacings. It is clear from visual inspection that, as well as a long-period 3-hour variation, there is more obviously a ~70-minute variation. The other two nights' results showed the same effect. Detailed Fourier analysis of the data showed that, as well as the originally known period of $2^h\ 55^m$, there is also a period of ~ 70 minutes present with possibly an exact period ratio of 2:5. (A more detailed paper containing all the results will be published elsewhere.) Figure 12 shows the mean ~ 70-minute light curve after removal of the $2^h\ 55^m$ variation. No night-to-night changes have been removed and all points are plotted. The r.m.s. scatter about the mean light curve is $\pm 0\overset{m}{.}0016$. When it is recalled that these results were obtained in sky conditions which were not even spectrographic, the power of comparative photometry should be clear.

4. The Present Status

The results from the two prototypes demonstrated both the potential increase in accuracy available from comparative photometry and the feasibility of using four separate detectors. Tests have been carried out on smaller diameter photomultiplier tubes than those originally used and models found which are useful. A development program has been completed to allow a container for four of these PMTs to be kept at a constant temperature of -28° at an ambient of $+15^\circ$ using Peltier coolers. A temperature controlled filter assembly has also been developed. Small high tension units matched to the requirements of the smaller PMTs have been built and tested and the necessary microprocessor electronics for counting and control is under active development. A new design of the four arm, focal plane part of the device, intended to be computer controlled with autocentering of the apertures is under development. It is intended to produce a batch of these photometers to allow multilongtitude observations to be carried out with identical devices. Tests on this latest stage in the development should take place in the winter of 1987/88.

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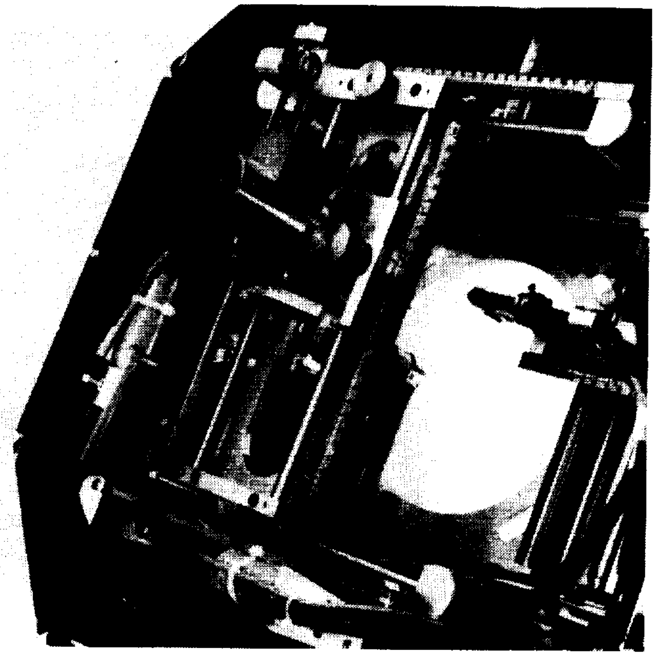

Figure 2 A close up of the travelling microscope above the four arms.

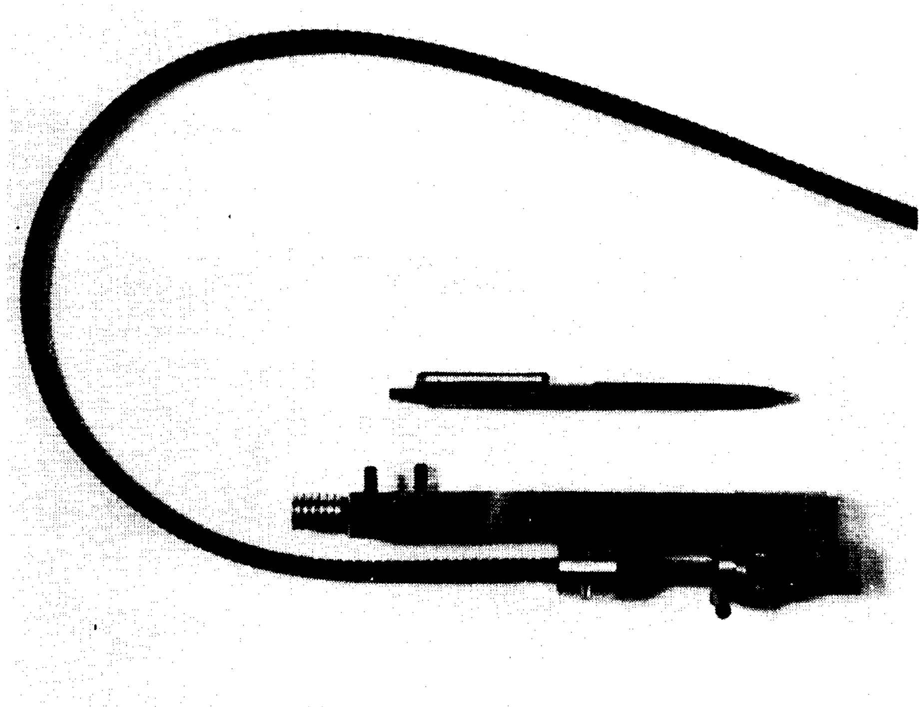

Figure 3 One of the four X Y arms with fibre optic bundle attached. The motion block is in the forward position deflecting light along the fibre.

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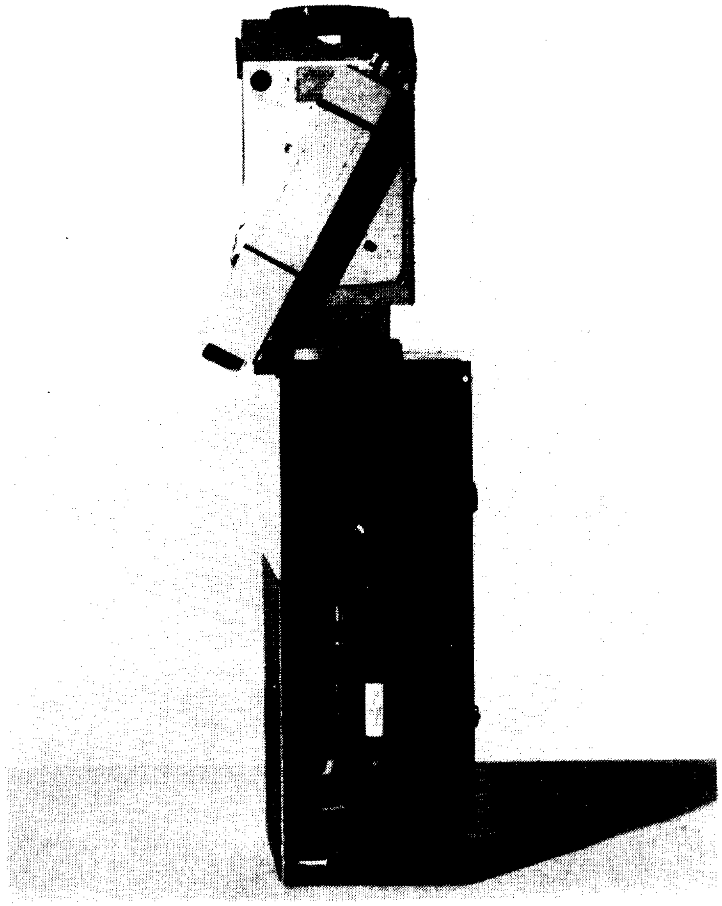

Figure 4 The chopper box assembly with the cold box and preamplifier/discriminator unit mounted above it. The chopper is contained within the lower face in this view and is driven by the motor via a flexible coupling. The four into one fibre optic integrator can be seen taking light from the chopper to the Fabry lens.

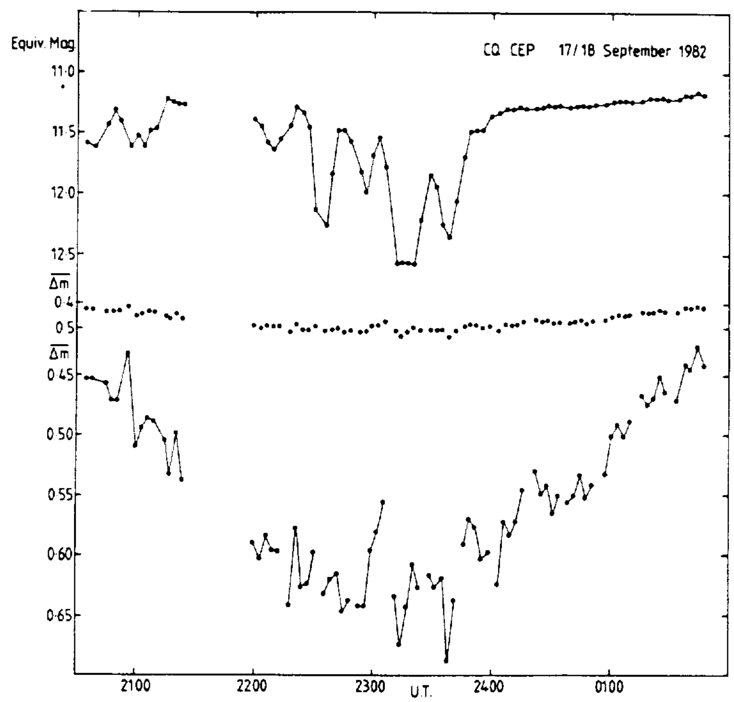

Figure 5 The upper diagram shows the variations in apparent brightness of CQ Cep. due to transmission changes in the sky plus changes intrinsic to the star. The middle plot shows the difference between CQ Cep. and two comparison stars, HD214259 and HD214220, on the same scale as the upper plot. The bottom curve repeats the data in the center plot but with the vertical scale increased by X10 in order to show the details.

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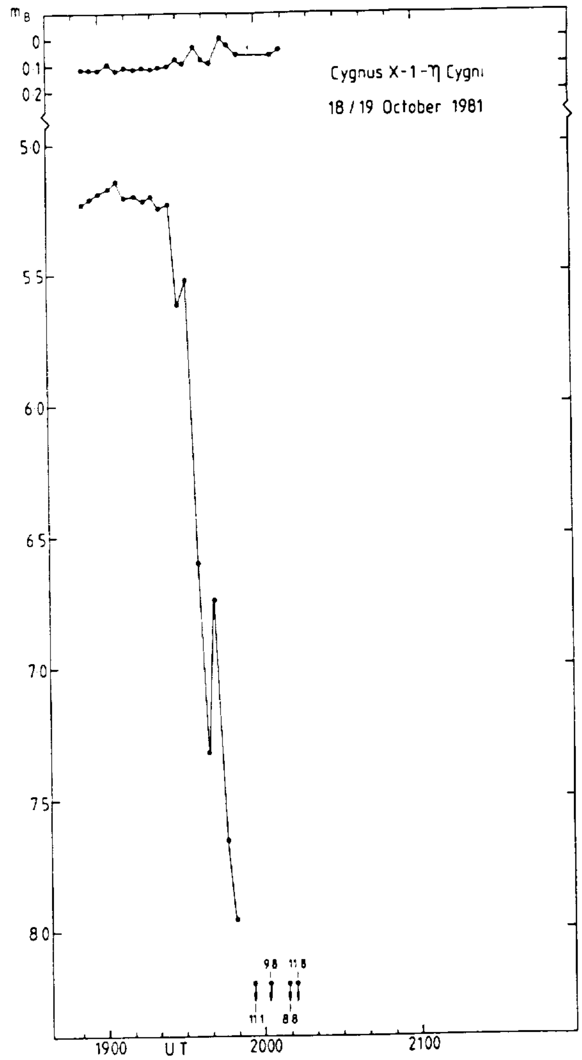

Figure 6 The lower curve shows the change in apparent brightness for η Cygni as the sky became cloud covered. The upper data show the change in mag. between η Cygni and HDE226868 (Cyg X-1) over the same time interval.

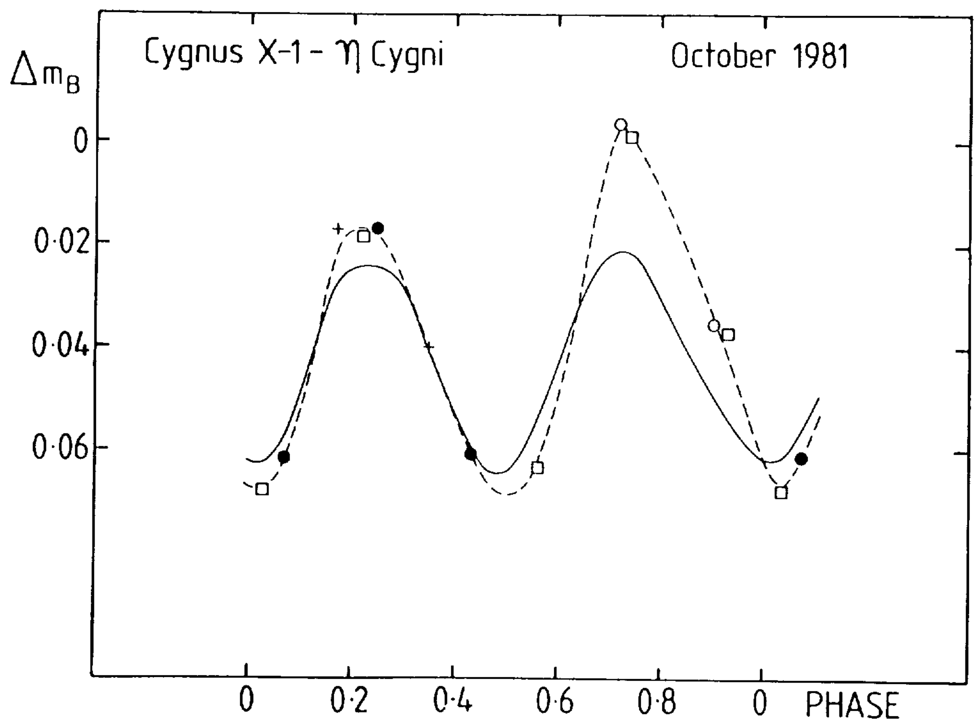

Figure 7 The solid line shows the mean light curve of HDE226868 (Cygnus X-1) derived from 9 years data. The dashed line is a hand drawn fit to 12 nights of data obtained through one lunation in October 1981. Different symbols represent data from different 5.6 day orbits. The data were obtained in a variety of conditions from cloudy to clear and from bright moonlight to no moonlight.

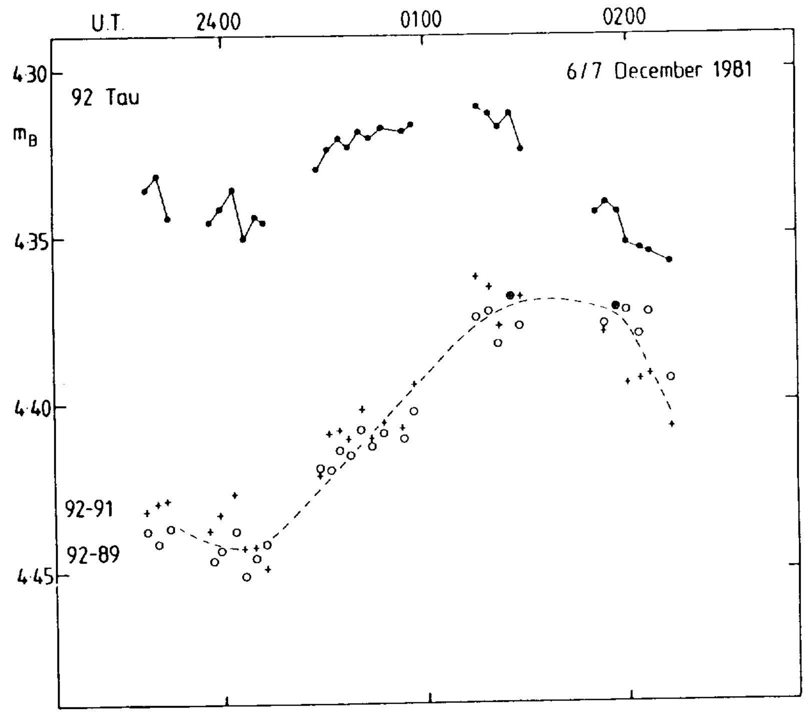

Figure 8 The upper curve shows the change in apparent brightness for 92 Tauri over ~2.5 hours due to intrinsic changes in the star and Sec Z effects. Below we show the differences in magnitude between 92 Tau and 91 Tau, and between 92 Tau and 89 Tau. These show the ~0.07 mag. change in 92 Tau during the observation.

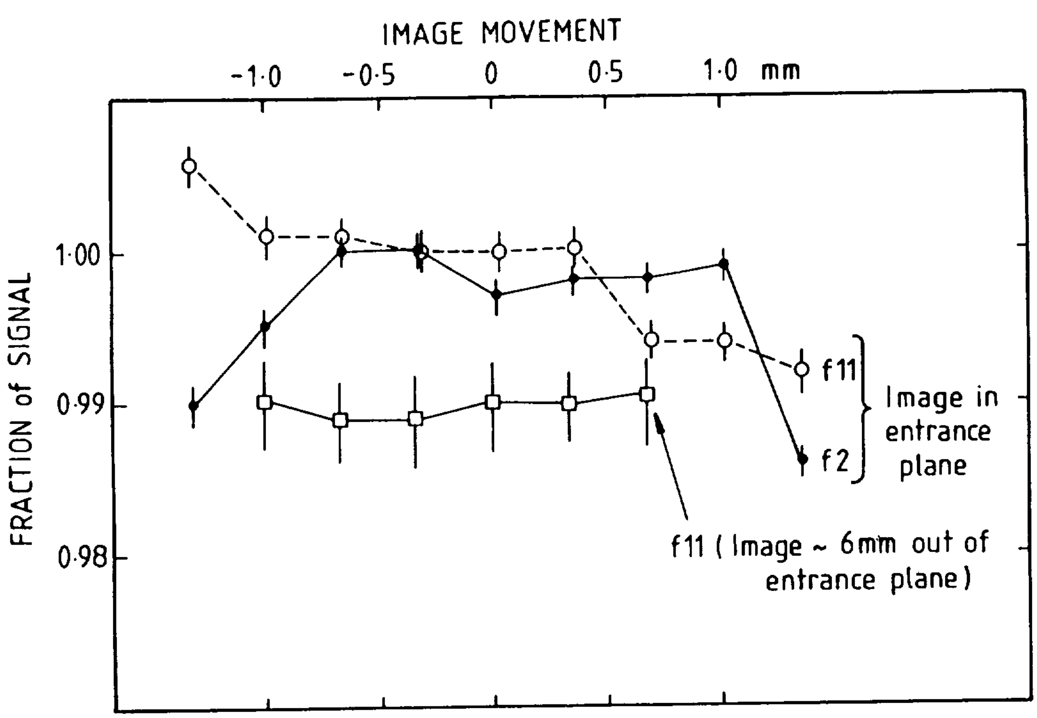

Figure 9 shows the changes in transmitted intensity as the input image was moved by 2 mm over the input end of a 3 mm diameter liquid light guide.

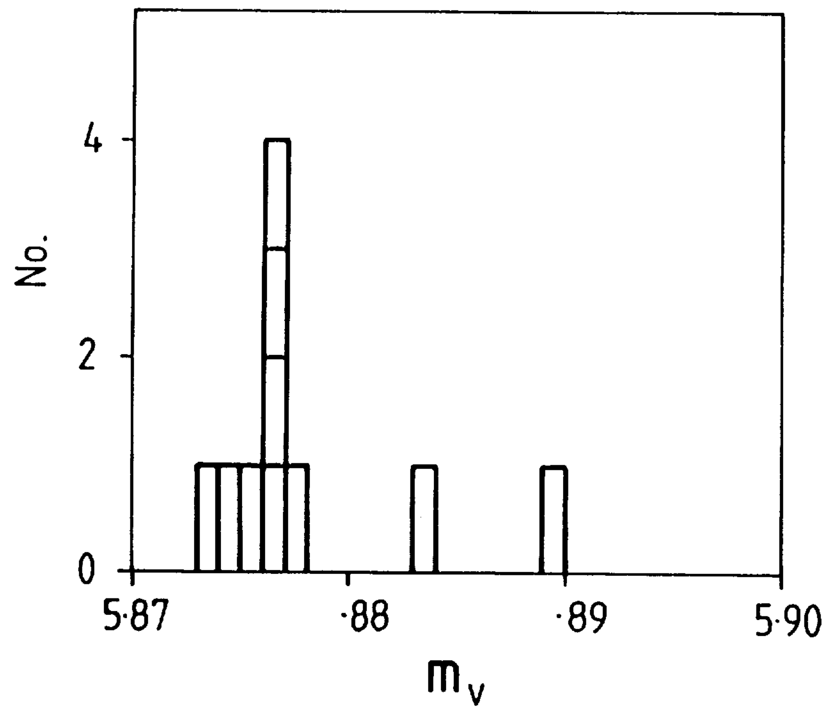

Figure 10 shows the measured magnitude of 27 Leo Minor over 3 hours in one night. The text describes the results.

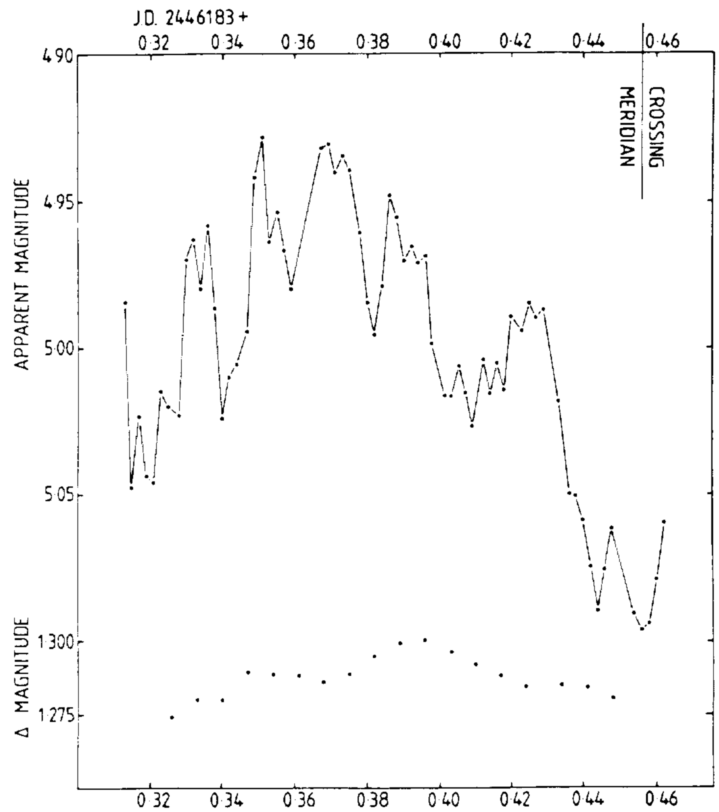

Figure 11 Upper curve is apparent B magnitude of 20 CVn with mean extinction removed. Note the effect of passing cirrus and final clouding up. Lower curve is simultaneous magnitude difference between variable and comparison. Note the 3-hour and the 70-minute variation.

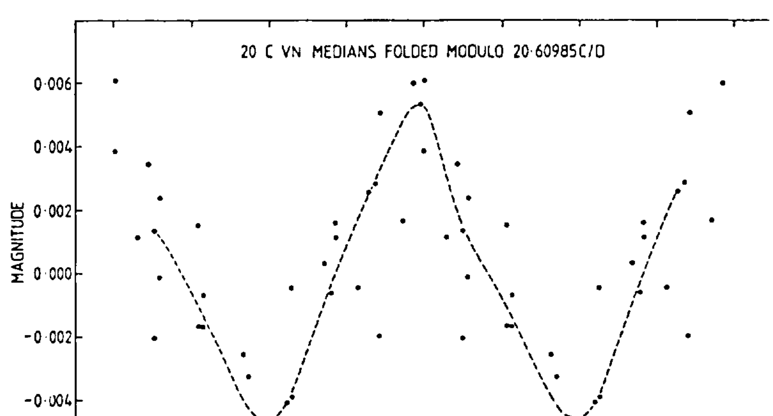

Figure 12 shows the mean light curve of 20 CVn using all 3 nights' data. A mean $2^h\ 55^m$ light curve has been removed but no other corrections have been applied. The r.m.s. scatter about the mean curve is ±0.0016 mags.