MULTICHANNEL MULTICOLOUR PHOTOMETRY: EXPERIENCES FROM A LONG TERM MONITORING CAMPAIGN

K.H.Mantel, H.Barwig
Universitaets-Sternwarte Muenchen
Scheinerstrasse 1
81679 Muenchen
Federal Republik of Germany

ABSTRACT. We present the design of a multichannel, multicolour photometer developed for the study of rapid variable objects like Cataclysmic Variables, Low Mass X-Ray Binaries, Burst Sources or Flarestars and discuss experiences from a long term observing campaign. It is demonstrated that high speed multicolour photometry with an accuracy on the millimagnitude scale can be achieved. The design of a new four channel spectrophotometer is presented which allows to treat correctly higher order extinction effects and which guarantees precise transformations to other standard photometric systems.

1. Introduction

The study of variable stars requires spectral- and time-resolved photometry. In order to gain insights into the underlying physical mechanisms responsible for the variability, information about the spectral behaviour on time scales typical of the system is needed. Depending on the nature of the variability (e.g. orbital motion, dwarf nova outbursts, quasiperiodic variations, period changes, amplification events, flares, bursts, etc.), the typical time scales of light variation phenomena range from years or days to minutes and seconds or even up to milliseconds. This implies that the equipment used must be stable and supply the observer with high accuracy multicolour data not only on short time scales, but also in the long run between different observing campaigns (which in some cases make use of different telescopes, e.g. for objects with periods in the range of multiples of a day). Therefore high accuracy of the single photometric measurement is needed as urgently as a stable and calibratable photometric system throughout the whole process of observations, data reduction and data processing. This includes not only control of all relevant instrumental parameters like quantum efficiency, deadtime, etc., but also careful monitoring of the sky background and the varying atmospheric transparency as well as optimized reduction procedures.

During the last years extended efforts including instrumental development and implementation of special adapted reduction procedures have been made by our

Fig. 1. Block diagram of the Multicolour-Multichannel-Photometer (MCCP).

working group at the Universitaets-Sternwarte Muenchen in order to install a photometric equipment which allows precise high speed multicolour photometry of rapid variable objects. As a result two multichannel photometric instruments have been developed together with comprehensive reduction software. A brief description of the Multichannel Multicolour Photometer (MCCP) can be found in chapter 2 together with experiences from long term observing campaigns. It is demonstrated that millimagnitude accuracy can be achieved with a multichannel fiberoptic photometer. In chapter 3 the design of the new Multichannel Spectrophotometer (MEKASPEK) is described. A 33 instrumental colour system is presented, which allows to treat higher order colour effects correctly. Results are summarized in chapter 4.

2. The Multichannel-Multicolour Photometer (MCCP)

This instrument was designed for high speed UBVRI-photometry of rapid variable objects. A block diagram of the instrument is presented in Fig. 1, details can be found in Barwig et al. (1). In the following a brief description of the instrument will be given. The main features can be characterized as follows:

- Simultaneous measurements of three different light sources (the object, a nearby comparison star and the sky background)
- Simultaneous UBVRI measurements of each light source covering the whole optical wavelength range with high efficiency
- High time resolution up to 20 milliseconds

2.1. INSTRUMENTAL DESIGN

Three optical fibers which can be positioned in the focal plane of the telescope within an area of 10x10cm transfer the signals of the three input channels to the entrance slit of three identical prism spectrographs. The fibers are fixed by an acryl plate where holes were drilled at the positions of the selected objects. The size of the measuring diaphragms can be selected between 0.6 and 1mm. The resulting spectra cover the region 3400-9000 Angstroem and are imaged onto an array of mono fibers. These arrays select 5 broad passbands and are optimized to match the Kron-Cousins UBVRI system as close as possible. 15 peltier cooled photomultipliers are used to record simultaneously the signals of the 5 UBVRI passbands of the three input channels. The multiplier signals pass the preamplifier and discriminator unit and are recorded and stored on disk by a microcomputer system. A CCD-camera in combination with an image intensifier can be positioned in the focal plane of the telescope for autoguiding.

2.2. MEASURING METHOD AND STANDARD REDUCTION PROCEDURE

During each integration the individual channels (1=object, 2=comparison star, 3=sky background) provide a combination of the following quantities for each of

Fig. 2. Sequence of the calibration coefficient in the colours UBVRI determined from comparison star measurements during a time interval of 3 weeks.

the 5 UBVRI passbands:

Channel 1 (object) : $TC(1) = O(1) + S(1) + D(1)$

Channel 2 (comparison star): $TC(2) = C(2) + S(2) + D(2)$

Channel 3 (sky background) : $TC(3) = S(3) + D(3)$

where $TC(i)$ is the signal measured in channel i, $O(i)$, $C(i)$, $S(i)$ and $D(i)$ are the intrinsic signals of object, nearby comparison star, sky background and dark current in channel i respectively (i=1,2,3). To a first approximation (so called *standard reduction*, see (1)) changes in atmospheric transparency and sky background contribution are the same for object and comparison star. Therefore the ratio $O(1)/C(1)$ gives the object signal relative to the nearby comparison star with extinction effects and contributions from the sky background removed. The simultaneous measuring method allows to determine $S(1)$ and $C(1)$ from the signals of the comparison star measured in channel 2 and the sky background measured in channel 3.

Due to different quantum efficiency of the different input channels additional calibration measurements are required. This can either be done with special calibration lamps or with the nearby comparison star and/or an additional standard star under photometric conditions. The measurements with calibration lamps have the adavantage of not consuming valuable observing time and may be performed even during day time. From these measurements calibration coefficients are determined which allow to transform the measured quantities from one channel to the other. These calibration coefficients also reflect the stability of the instrument and instrumental changes (transmission, efficiency). Figure 2 shows the calibration coefficient for the transformation of the comparison signal from channel 2 to channel 1 in the UBVRI colours determined in different nights from calibration measurements using the comparison star. Individual nights are seperated by vertical lines. The typical error of each calibration coefficient amounts to 0.3% to 0.5% depending on colour and is marked as a vertical error bar. These errors are probably due to improper centering of the comparison star in the entrance diaphragm. Except in the V passband the individual variations are smaller than the typical errors, therefore mean values of the calibration coefficients can be used for the reduction to improve the accuracy. In this case the error of the coefficients can be reduced to 0.05% in B and less than 0.2% in the other colours. Between night 2 and 3 a powerfail caused a change in the efficiency of the multiplier used for the V passband in channel 2 which resulted in a change of the transformation of about 4.2%. The data clearly demonstrate, that the calibration of a multichannel photometer with an accuracy of better than 0.2% is feasible. The standard reduction is a powerful tool to reduce atmospheric extinction effects, transparency variations up to 80% can be corrected (for an example see chapter 3, Fig. 6). Details of the procedures as well as an extensive discussion of the standard reduction, its involved assumptions and errors depending on brightness of object, comparison star and sky background can be found in (1).

2.3. ITERATIVE REDUCTION PROCEDURE

Besides applying the standard reduction data can also be reduced in a more conservative way: sky background and dark current contribution are subtracted from the object and the comparison channel. From the comparison star data measured during photometric conditions extinction coefficients and extraterrestric countrates for the comparison star are derived. The extinction coefficients are used to reduce all object and comparison star data to zero airmass, residual variations in the comparison star data are used to correct transparency variations in the object measurements. The transformation to the UBVRI system is determined from photometric standard star measurements. This reduction procedure requires photometric conditions, otherwise extinction coefficients and extraterrestric countrates are determined systematically too small. In order to solve this problem the so called *iterative reduction procedure* was developed, which allows to determine extinction coefficients and extraterrestric countrates with high accuracy even in nights with varying transparency (2).

Fig. 3. Measurement set of the comparison star (sky background and dark current subtracted) during a non-photometric night (above), data obtained during photometric conditions are marked by bold points. The mid pannel shows the Bouger line fit for the data under photometric conditions. Residuals between ideal and measured data are shown below.

TABLE I
Extraterrestric magnitudes of the comparison star in different nights.

Night/Colour	U	B	V	R	I
27.10.90	9.2734	7.9307	8.6209	9.1926	10.5371
28.10.90	9.2850	7.9298	8.6188	9.2067	10.5647
29.10.90	9.2808	7.9343	8.6280	9.1940	10.5408
30.10.90	9.2605	7.9302	8.5931	9.1512	10.5432
31.10.90	9.2881	7.9418	8.6409	9.2046	10.5920
mean	9.2776	7.9316	8.6226	9.1978	10.5475
error	+-0.0110	+-0.0050	+-0.0175	+-0.0225	+-0.0230

The interactive reduction procedure starts with a first guess for extinction coefficients and extraterrestric countrates (determined in the classical way from all measurements, including those under non-photometric conditions). For these values a theoretical, ideal data set can be computed. Deviations between the theoretical and the measured data set are caused by atmospheric transparency variations, which prevent a correct determination of the extinction coefficents and the extraterrestric countrates. The deviation for each datapoint between the ideal and the measured data set is used to assign a weight to each measured data point depending whether it lies above or below the theoretical value. In the next iteration step new values for the extinction coefficients and the extraterrestric countrates are derived from the weighted measurement data set. In this way measurements obtained under photometric conditions are extracted from the data and even in nights with only small parts of measurements under photometric conditions reliable extinction coefficients and extraterrestric countrates can be determined. Figure 3 shows a set of measurement data of the comparison star corrected for sky background and dark current, obtained in a non-photometric night together with the classical Bouger line determined from data obtained during photometric conditions and the ratio between ideal and measured data.

Table 1 gives the results of extraterrestric magnitudes of the comparison star determined by use of the iterative reduction procedure during five non-photometric nights.

As a result even in *non-photometric* nights extraterrestric countrates of the comparison star and extinction coefficients can be determined with an accuracy between 0.5% and 2% *without* any additional standard star measurements. The lower accuracy in the R and I band is caused by the diminished quantum efficiency of the photomultipliers in these wavelength regions.

2.4. ACCURACY IN LONG TERM MONITORING

In order to demonstrate the accuracy obtainable with a multichannel multicolour instrument the final reduced light curve from a long term observing program is shown. The aim of this program was to determine the physical parameters of the hot binary system DN Cas. Due to the 2.3 days orbital period of DN Cas, data of different nights had to be combined in order to cover the most important parts of the

Fig. 4. Reduced light curve of DN Cas (marked by '+') together with the best fit derived from theoretical models (straight line). The error of the individual data points is 0.001 to 0.002 mag.

light curve. During 3 years 14 nights of data were obtained with the MCCP at the 0.8m telescope of the Wendelstein Observatory with a time resolution of 4s. Figure 4 shows the final reduced light curve together with a best fit derived from theoretical models. Data were binned to time intervals of 8 minutes resulting in count rates of more than 5e7 counts per time interval, therefore the poisson statistics should not contribute to the error of individual data points. The remaining error of individual measurements is 0.001 to 0.002 mag (3), (4). Extensive investigations were made in order to determine the source of this remaining error. As the most probable error source the size of the input diaphragm was identified. During the observations a size of 16" was used, which in case of slightly improper centering might cause an error on the millimagnitude level.

Although the multichannel multicolour photometer proved to be a reliable and stable instrument the following problems remain:

- the size of the entrance diaphragms is limited to 1mm in diameter
- second order extinction effects are neglected by the reduction procedure
- fiber positioning requires the exchange of a mask and is therefore time con-

suming

– transformations to the standard system involve errors of the order of 3-5%

Therefore in 1987 the MEKASPEK project was started, which aimed to develop an instrument which overcomes these problems.

Fig. 5. Block diagram of the Multichannel Spectrophotometer (MEKASPEK).

3. The Multichannel Spectrophotometer (MEKASPEK)

3.1. INSTRUMENTAL DESIGN

The MEKASPEK instrument is a four channel fiberoptic spectrophotometer which allows to measure 4 sources simultaneously with a spectral resolution of about 50 in the optical wavelength range between 3500 and 9000 Angstroem. Figure 5 shows a block diagram of the instrument. Four fiber bundles can be positioned by computer control in the focal plane of the telescope. A Fabry lens at the entrance of the fiber bundles projects the entrance pupil of the telescope onto the circular fiber bundle with a diameter of 0.2mm. The diameter of the entrance diaphragm can be changed between 0.6 and 2mm. The rectangular exit of the fiber bundles form a homogenous illuminated entrance slit of a prism spectrograph. The spectra of the four sources are imaged onto the photocathode of a two-dimensional, photoncounting detector (MEPSICRON, (5)) and are recorded by a realtime multitasking VME-Bus computer system. A maximum time resolution of 20ms can be achieved. Instrumental details can be found in Mantel, Barwig and Kiesewetter (6).

3.2. MEASURING METHOD AND DATA REDUCTION

The measuring method is similar to that applied for the MCCP besides the fact, that with MEKASPEK an additional fiber is available, which can be used to monitor a second comparison star (e.g. with a different spectral distribution) for improved description of colour dependent extinction effects, or in cases of dominant straylight (moon), can be used to monitor the sky background at a second position to compensate for spatial varying background contribution.

An example for the elimination of atmospheric transparency variations is shown in Fig. 6. The upper two panels show the measurements of an eclipsing cataclysmic variable and a nearby comparison star during a period were strong cirrus caused large transparency variations up to 90%. In the lower panel the reduced lightcurve (standard reduction applied) is shown. Most of the transparency variations could be reduced completely, only during times of verly low transparency the scatter in the reduced lightcurve is increased due to photon noise.

3.3. DETERMINATION OF HIGHER ORDER COLOUR EFFECTS

All photometric reduction procedures suffer from insufficient knowledge of the spectral distribution of the observed stars. This implies that second order extinction effects can be treated only in a very crude way and limit the accuracy obtainable so far (for an excellent review of this problem see (7)). This problem is solved with MEKASPEK: flux-calibrated low-resolution spectra provide the necessary information on the spectral distribution of the observed objects and allow to treat higher order extinction corrections. In general the influence of atmospheric extinction on the measurement within a passband can be described by (cf. (2)):

Fig. 6. Standard reduction applied to object data obtained during strong transparency variations. Original data of object and comparison star are shown in the upper and mid panel respectively. In the lower panel the reduced light curve is displayed.

$$C(t) = I(t)A(t)(1 + x)F$$

where:

C(t) recorded count rate

I(t) extraterrestric flux of object

A(t) atmospheric extinction

x correction term for higher order colour effects

F integral of filter curve of passband used

All the higher order extinction effects are described by the x-term which includes airmass, moments of the passband used and also the first and second order deriva-

Fig. 7. Instrumental 33 colour system with widely overlapping filtercurves.

tives of extinction coefficients and spectral intensities. Typical values of this term depend on the combination of the spectral distribution of the object and the filter passbands used and may range between 0.0001 and 0.1. Small values of x indicate a well adapted description of colour effects by the photometric system used.

Due to the limited spectral information provided by photometric standard systems, only crude approximations could be derived for the derivatives involved in the x-term so far. Because of the spectral resolution, the MEKASPEK data now enable to solve this problem and allow a numerical determination of the derivatives involved.

This is accomplished by summing up data in widely overlapping filter passbands, which fulfil the sampling theorem. Intensities of these overlapping passbands can be used to describe derivatives in a proper way. Therefore higher order extinction effects can be treated correctly. Additional software was developed which allows to determine the x-term numerically from the intensities of all the neighbouring filter passbands, by using an approximative spline function, fitted to the intensities obtained in the overlapping filter passbands. Details can be found in (2).

An example for this is shown in Table 2: the measurement data where summed up into 33 widely overlapping passbands (see Fig. 7), which fulfil the sampling theorem. For each passband the x-term was computed. As can be seen from Table 2 the x-term is usually below 3%, only on the very blue and red side higher correction terms appear. The reason for this an insufficient description of the derivatives due to low efficiency of the instrument in these wavelength regions. The low values of the correction term show, that higher order colour effects are well described by an instrumental system with widely overlapping filtercurves.

Transformations to other broad band standard systems also profit from the correct description of higher order colour effects. Due to the widely overlapping filtercurves colour terms in transformation equations can be neglected and colour transformation can be calculated from the instrumental filtercurves. The filtercurves of the 33 instrumental colour system have been measured using a flux-calibrated scanning monochromator (see Fig. 7). From these filtercurves transformations to the Kron- Cousins UBVRI, the MCCP and the Stroemgren colour system have been calculated. Figure 8 shows the filtercurves of the UBVRI system together with a fit calculated from the transformation. The bad approximation in the U- and I-band is caused by the low quantum efficiency of the detector in this wavelength region. The excellent approximation in the other colours demonstrates, that an instrumental colour system with widely overlapping filtercurves fitting the requirements of the sampling theorem allows precise colour transformation to broad band standard systems.

4. Conclusions

Millimagnitude accuracy can be achieved with multichannel multicolour photometry. Due to the simultaneous measurement of a nearby comparison star and the sky background transparency variations up to 80% can be compensated. The multichannel spectrophotometer allows to calculate accurate transformations to all broad band photometric systems.

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Fig. 8. Approximation of the UBVRI-system.

TABLE II
Correction term x computed for a 33 colour photometric system.

filter	cen.wavelength	x-term	filter	cen.wavelength	x-term
1	4150	1.0450	18	5803	0.9948
2	4161	1.0222	19	5920	0.9942
3	4191	1.0106	20	6048	0.9935
4	4256	1.0044	21	6186	0.9930
5	4346	1.0007	22	6342	0.9923
6	4454	0.9983	23	6512	0.9914
7	4575	0.9969	24	6692	0.9904
8	4717	0.9961	25	6892	0.9887
9	4848	0.9961	26	7113	0.9857
10	4983	0.9961	27	7366	0.9799
11	5138	0.9964	28	7638	0.9711
12	5283	0.9972	29	7933	0.9587
13	5352	0.9970	30	8227	0.9434
14	5427	0.9968	31	8528	0.9331
15	5508	0.9963	32	8874	0.9285
16	5598	0.9959	33	8953	0.9198
17	5696	0.9953			