COMMISSION 25. STELLAR PHOTOMETRY AND POLARIMETRY
PHOTOMETRIE ET POLARIMETRIE STELLAIRES

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1. INTRODUCTION

Technology has continued to influence the methods of stellar photometry and polarimetry in the last triennium. For example, CCDs continue to displace photographic plates in stellar photometry and other detector systems for imaging and spectro-polarimetry, new array detectors for infrared wavelengths have revolutionised the way infrared photometry and polarimetry is done and small automatic telescopes and robotic observatories have experienced a remarkable growth period. The volume of data to be archived and transformed to "standard" systems has become immense and all the problems of inter-comparing different systems still remain.

Increasing experience with Stromgren and other intermediate- and narrowband systems has shown that not all the difficulties with the UBV system were due to bandwidth. Difficulties with transformations to a standard system are becoming increasingly prominent, especially as observers try to duplicate existing systems with new detectors like GaAs photocathodes and silicon CCDs. The intercomparison of photometers and photopolarimeters in space (e.g., on HIPPARCOS and HST) with ground-based systems presents still further problems. The need to obtain continuous coverage by combining data from different observatories has also involved transformation problems, blurring the line between precision and accuracy. Precision and efficiency are often bought, at the expense of complexity, with multi-channel instruments. Intercalibration of the channels again raises the transformation problem. These concerns also extend to the near infrared.

CCDs now dominate faint-star work, where time-dependent sky brightness and scarcity of photons put conventional photometers at a great disadvantage. On the other hand, their limited dynamic range and long readout time, together with difficulties in flat-fielding point sources to better than 1%, leave photomultipliers the advantage in bright-star photometry, especially that requiring the highest accuracy. At intermediate brightnesses, between about magnitudes 10 and 15, CCDs are more efficient for crowded fields. Of course, the small size of available devices leave photographic plates unchallenged for wide-field survey work with Schmidt cameras.

Because of the huge volume of work being published, we cannot aim for completeness, but can present only a Durchmusterung of the literature, mentioning some essential works and giving samples of the most active areas; polarimetry is particularly well "integrated" and finds numerous applications throughout astrophysics. References are given in terms of the volume and citation number in Astronomy and Astrophysics Abstracts. Crawford's historical review (46.004.052) is a guide to the classical literature of photometry and the recent book by Coyne et al. (1990) provides an excellent reference for polarimetrists.

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2. PHOTOMETRY

2.1. Instrumentation

2.1.1. Photometry With Scalar Detectors

Photomultipliers continue to dominate this field. The technology is mature, and good housings, power supplies, and signal-processing electronics are available commercially. The main technical advances are computer control of these instruments, ranging from automatic recording of filter and diaphragm positions of a manually-operated instrument along with time and signal value, to fully automatic operation, including finding and centering stars. Dozens of descriptions have been published; the Sutherland photometer (46.034.007) is a well-described example that represents current practice. Magnitskii (49.036.048) offers a variety of instrumental improvements.

Many multi-channel instruments have been described. The most ambitious project in this direction is Barwig's; the instrument (43.034.103) involves 15 channels (one each for program star, comparison star, and sky, in UBVRI simultaneously) fed by fiber optics. Its performance has been reported (46.034.260), and a second-generation instrument (49.034.202) is planned. Walker (46.034.262) describes a 4-channel instrument, also using fiber optics. (A book on fiber optics in astronomy has been published: 46.012.080.) The performance of an older multi-channel photometer, URSULA, is also reported (49.034.259) in the proceedings of the Second Workshop on Improvements to Photometry (49.012.098).

Several photometers are optimized for "high-speed" photometry; this term seems to mean anything faster than one data point on the program object per minute. Warner's book (46.003.142) describes both the technique and its applications. The instrument used successfully by the group at the University of Texas to study white-dwarf oscillations uses photomultipliers (46.034.107); it is challenged by a CCD version (46.034.094). The former paper compares the two. Nather has combined data from several such instruments in a global network he calls the Whole Earth Telescope (49.036.157). The high-speed photometer on HST (46.035.116) was intended for higher time resolution, in the sub-second range obscured by scintillation noise on the ground. Stecklum (43.034.141) also discusses high-speed photometers, and Schoembs (43.034.228) discusses the need for high time resolution. Some instruments have less conventional detectors. A group at the Crimean Astrophysical Observatory have extended their use of television systems with a multipurpose instrument (49.034.192) that can do B, V, or R photometry to 20th magnitude on a 50-cm telescope, or simultaneous 4-color photometry to 15th. Borucki's group is developing a multichannel instrument using silicon photodiodes (46.036.240, 49.035.064) to reach sub-millimagnitude precision. By using silicon diodes in the photoelectron-bombarded mode, it may be possible to do photon counting with higher instrumental stability than photomultipliers offer (46.36.103); but the system tested suffered from nonlinearity.

Nonlinearity is a problem with other detectors. The ESA PCD's linearity problems are discussed by van Heerde (46.034.127). Homberg (46.034.022) shows how to correct the nonlinearity of photographic emulsions by assuming a constant point-spread function. Even CCDs sometimes show this problem; Stetson et al. (49.154.046) give an example, and show how they correct it.

Three publications deal with light losses due to poor centering in small diaphragms. Magnitskii (45.113.050) finds that the diaphragm size should be 7 to 10 times the apparent seeing disk. Cousins (46.031.078) shows traces of a star across a diaphragm, and Caldwell (49.031.084) attempts to simulate such traces with a Gaussian seeing disk. Unfortunately, the actual light losses are much larger than this would suggest, because the wings of the star image fall off with a very low power law (-2 or -3).

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Another long-standing problem is temperature effects in photometry. Park and Chen (49.113.009) have found larger temperature effects in observational data than those predicted some years ago by Young from laboratory measurements (see also 49.034.235).

2.1.2. Photometry With 2-D Detectors

Once again, numerous conference proceedings contain papers on the operation and applications of CCDs. These include the ESO-OHP Workshop (43.012.016), several papers in Optical Engineering (44.034.201-207), the joint commission meeting from the last General Assembly (49.002.110 and following papers in "Highlights," vol. 8), the conference proceedings, "CCDs in Astronomy. II," just published, and vols. 865 (46.012.059) on focal-plane arrays, 891 (46.012.063) on polarization, 1071 (49.012.051) on electronic photography, and especially 1235 -- Instrumentation in Astronomy VII -- of the SPIE Proceedings. The meeting on image detection and quality (44.012.079), and Chapters 5 and 8 of McLean's book "Electronic and Computer-aided Astronomy; from eyes to electronic sensors" (49.003.046) also contain practical advice.

All array detectors, including CCDs, are inherently undersampled, so one must make sure the optical point-spread function covers enough pixels to avoid aliasing errors. The intrinsic MTF of several CCDs has recently been measured by Feltz & Karim, Appl. Opt., 29, 717 (1990).

Much of the difficulty in getting good photometry from CCDs comes from flat-fielding errors. Stetson's papers (46.154.10, 49.113.059) discuss this and other problems of CCD photometry. Frandsen et al. (49.153.015) find errors apparently due to imperfect flat-fielding of one or two per cent in differential photometry if the stars are placed at random on the chip, but much smaller errors if the image position is carefully held fixed.

Optimal extraction of faint stars requires PSF models. Bendinelli et al. (49.036.074, 075, and 243) have put much effort into using PSF models to extract stars from crowded fields. Mighell (49.036.147) has taken a different approach to the same problem. Stetson's widely used package DAOPHOT (43.036.085) has recently been ported to IRAF. The MIDAS system is available for both VAX/VMS (46.036.117) and UNIX (49.013.053) systems. These and other systems are compared in the Proceedings of the ESO data-reduction workshop.

Despite the emphasis on CCDs, photographic photometry is far from dead. An IAU Workshop on Astrophotography (46.012.019) covered topics like hypersensitization that formerly were in the AAS Photo-Bulletin. Wesselink (49.036.247) points out that the best photographic photometry can be transformed fairly accurately to the B,V system and is still useful. Indeed, the Guide Star Catalog for the HST (44.002.044) contains some 19 million stars with photographic magnitudes accurate to about 0.3 mag (see June 1990 A. J.), determined from Schmidt plates and calibrated by B,V photoelectric photometry (46.002.089) of 1477 sequences of 6 stars each. Photography continues to be essential for wide-field work with Schmidt cameras; our members may be interested in the procedures used for the new Palomar Sky Survey (46.034.031).

2.1.3. Automated Photometry With Robotic Telescopes

This topic has been advanced by Genet and his collaborators, with publications not only in the IAPPP Communications (e.g., 43.032.021) but also in a series of conference proceedings (43.012.030, 45.012.047, 49.003.052) and other publications (44.013.031, 45.003.002, 49.003.016). Saul Adelman is coordinating a joint Commission 25 and Commission 9 meeting on Automated Photometry for the next General Assembly.

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2.2. Extinction and Transformation

The papers from the joint commission meeting on these topics at the last General Assembly have now been edited by Milone and published as Vol. 341 of Springer Lecture Notes in Physics. Although the emphasis was on the infrared, many of the papers are of general interest.

In the visible two groups of problems are being discussed. The first concerns the bands VRI. Bessell (43.113.009, 44.113.014) has continued his series of papers on this subject. In the latter, he finds that cubic transformations are necessary. This is confirmed by Taylor et al. (49.113.008) who point out that this is due to the asymmetry of the standard bands, especially R, that are limited by the tail of the photocathode response. The more symmetrical filters used with CCDs and GaAs cathodes produce data that require a cubic term to transform to the asymmetrical standard band.

The second problem concerns uvby transformations. Manfroid and Sterken have continued their investigations of difficulties in this system (44.113.024, 45.036.090), finding in the latter paper that the apparent evolutionary status of the Beta Cephei stars depends on the filter set used. The problems in converting between "slot" and "filter" uvby systems are further confirmed by the Vilnius workers (45.113.039).

Young (46.113.044) has looked into the effect of system design and data-reduction algorithms on the accuracy of extinction correction. He finds that, while large modelling errors occur in existing systems, King's model can provide extrapolation to outside the atmosphere with sub-millimagnitude accuracy if the sampling theorem is respected. This requires centering successive bands about halfway down the sides of their neighbors.

Numerous measurements of extinction at various sites have been published. Several deal with the Saharan dust problem in the Canary Islands. Whittet et al. (44.082.039) model the dust observed at La Palma; Andrews and Williams (49.082.069) emphasize that it is not neutral, but slightly reddening. Kidger (46.082.061) extends this into the infrared, for the dust observed from Tenerife; Andersen et al. (46.082.039) show that it has a consistent diurnal variation. It is not generally known that the Carlsberg meridian circle on La Palma routinely gathers extinction data as well as positional information; the extinction values, which are of considerable climatic value, are buried in an obscure annual report that should be available from the observatories involved.

Krisciunas et al. (44.082.042) report extinction at Mauna Kea. Angione (44.082.043) gives extensive data on precipitable water above Mt. Laguna, California, not far from Palomar Mountain. Nikonov et al. (49.082.064) show time variations in the light entering telescopes in the Crimea; the short-term fluctuations they show are probably due to scintillation, and the slower ones to genuine extinction variations. Nicholls (46.082.020) gives examples of theoretical models for both atmospheric and interstellar extinction.

2.3. Photometric Systems

2.3.1. UBVRI

Note the continuing difficulties in transforming R and I mentioned in the last section. Mermilliod has listed (43.002.076) and analysed (44.002.030) discrepancies exceeding 0.2 mag. in the 1986 UBV catalog, which is available on magnetic tape (44.002.031). Some of these stars need further observations. New standard sequences continue to be published, especially faint stars for CCD use: a set of B and V sequences covering all galactic latitudes to mag. 22 (43.113.008); zero-point stars for the Magellanic Clouds (43.156.020); UBVRI for Cloud clusters (45.113.024); and a revision of Cousins's Magellanic Cloud standards (44.113.043). Menzies et al. (49.002.086) have published UBV(RI)c E and F region standards. Kilkenny and Menzies (49.113.039) give UBVRI photometry for the secondary spectrophotometric standards used in the Southern Hemisphere. Note also the BV sequences mentioned above (46.002.089).

2.3.2. Stromgren

Cousins (43.113.046, 44.113.044) has measured the E-region standards in the Stromgren system, and has also established secondary H-beta standards in the E regions (49.113.038). He has also established relations between (b-y) and (V-Ic) (44.113.019). We note that he has recently retired, but continues to produce work that benefits the rest of us. Let us wish him a happy and -- for our sake -- a productive retirement!

Perry *et al*. (44.002.104) have published a catalog of bright uvby-beta standard stars. Although Cousins reduced the internal errors of his H-beta standards to a millimagnitude, the external discrepancy with the Perry catalog is 0.005 mag. This suggests that transformation problems are not confined to wideband photometry.

2.3.3. Infrared

Bessell and Brett (46.113.023) discuss the JHKLM system. Minikulov (44.113.032 in Russian; 49.113.050 in English) has selected the best 2-color diagrams that can be constructed in the UBVRIJHKLM system for various purposes. Tapia *et al*. (44.113.030) have published standards for the J to M bands. We may note also the IRAS catalog of small sources (46.002.182).

2.3.4. Others

Work continues in the Geneva, Walraven, DDO, Washington, and many other systems. Catalogs have recently been published for the Geneva (49.002.035) and Vilnius (44.002.090) systems.

New special-purpose systems continue to proliferate. We may mention the "77-81" system (49.113.002) for late-type (M and C) stars, and the Utrecht Photometric System (49.113.037) of narrow continuum bands, intended for use on eclipsing binaries. Horne (46.036.320) and Edvardsson and Bell (49.113.031) discuss at length the relations between the HST filters and existing ground-based systems, using synthetic photometry.

2.4. Synthetic Photometry and Spectrophotometry

Synthetic photometry is becoming a powerful tool for studying existing and proposed photometric systems, now that spectrophotometric data have become reliable enough to use in this way. Crawford (45.113.029, 46.036.321) has discussed this technique, and Buser (46.115.031) mentions it in his article on photometric surveys. We have already mentioned its use to study the HST filter systems, and Minikulov's use of synthetic photometry in studying 2-color diagrams. Weisz and Bell (49.113.061) have used it to compare the original 1P21 BV system with CCD BV systems. Young (46.113.044) used it to investigate the accuracy of extinction modelling.

Spectrophotometry continues to produce more information about stellar spectra. The proceedings of the conference on "New Directions in Spectrophotometry" (46.012.090) should interest our members. Spectrophotometry of 25 stars with mostly smooth, featureless spectra (45.113.034) is intended by Massey *et al*. to provide calibration spectra useful at different spectral resolutions. There is also the Sternberg Observatory spectrophotometric catalog (49.002.038) and some spectrophotometry of 50 carbon stars (46.002.087).

2.5. Catalogs and Data Bases

Data management is described in C. Jaschek's book, "Data in Astronomy" (49.003.019). The problems of maintaining photometric databases are discussed by Heck and Manfroid (46.002.041) and C. Jaschek (49.002.111). It is essential to keep all the individual observations and their times, in case a star turns out to be variable; homogenized mean values are not enough. The SIMBAD database (46.002.038) is now widely available. The HST Guide Star Catalog was mentioned above, under two-dimensional photometry. Mermilliod (43.002.076, 45.002.030) has published lists of stars with grossly discrepant data (differences over 0.2 mag), some of which should be investigated further.

In addition, the photometric experiment TYCHO on the HIPPARCOS satellite has been described (45.036.002, 46.012.040, 46.036.022). Ground-based UBVRI data are available for the HIPPARCOS input catalog (46.113.026).

To make computer-readable catalogs more widely available, the FITS (flexible image transport system) standard has been extended to accommodate tabular material (45.036.122, 123 and 49.036.266).

The Vyssotsky centennial (49.012.092) provides a guide to catalogs. The uses of large databases, and descriptions of many that are now available, are discussed in another conference proceedings (46.012.015). Catalogs and other files available from the CDS are listed in a series of reports (44.002.094-096, 45.002.113-115, 49.002.136 and 137). The Astronomical Data Center (44.002.042) publishes a Bulletin that keeps users informed of their holdings. A Soviet Data Center has also been briefly described (44.013.080).

3. POLARIMETRY

3.1 Introduction

Astronomical polarimetry has continued to expand in the last triennium. New photoelectric multichannel polarimeters for high precision work on point-source objects have been introduced, and CCDs have provided the 2-dimensional detector needed for imaging polarimetry and spectropolarimetry. Exceptionally high precision has been obtained in polarimetry of the Sun and many high polarization "standard" stars have been studied carefully for intrinsic polarization effects; however, a uniform set of polarization standard sources still remains a problem. Infrared polarimetry has also blossomed in the same period due partly to the advent of infrared array detectors for the wavelength range 1 to 10 microns. Optical and infrared polarimetric instruments are briefly reviewed in the context of the applications of CCDs and infrared arrays, in the book by I.S. McLean, "Electronic and Computer-aided Astronomy; from eyes to electronic sensors", published by Ellis Horwood Ltd., Chichester, England (ISBN 0-7458-0205-2).

There have be no conferences dedicated solely to polarimetry in the past three years. Rather, a survey of Volume 49 of Astronomy and Astrophysics Abstracts reveals that polarization has wide-spread applications in many areas of study and is an "integrated" tool. For example, polarimetry is used in the study of Active Galactic Nuclei (49.158.327), Algol systems (49.119.073), AM Herculis stars (49.117.031 .054 .092 .200 .248), Be stars (49.112.049 .121), Interstellar Matter (49.116.022), Late-type stars (49.116.035 .064), Magellanic Clouds (49.156.036), Reflection Nebulae (49.131.008 .009 .108), T Tauri stars (49.121.003 .006 .049), Wolf-Rayet stars (49.116.011 .049) and many others. An excellent review of many polarization studies is to be found in the 795-page book edited by G.V. Coyne *et al.* entitled "Polarized Radiation of Circumstellar Origin," published in 1990 by University of Arizona Press, Tucson, USA (ISBN 8165-1120-9). A joint commission meeting with Commissions 9, 27, and 42 on the "Contributions of Polarimetry to Stellar Astrophysics" is planned for the 1991 General Assembly.

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There is, however, one sad note. Shortly before the Baltimore General Assembly, we heard of the death of James C. Kemp of the University of Oregon. Jim was well-known to the astronomical community in general and to polarimetrists in particular. He developed the photo-elastic modulator or PEM, a polarimeter with no moving parts in which phase retardations were caused by stress-induced birefringence in a large crystal. Among his many accomplishments are the discovery of interstellar circular polarization, grey-body magneto-emission from white dwarfs, circular polarization from planets and phase-locked polarization in x-ray binaries; he also demonstrated the detection of polarization at a level of 1 part per million in solar studies. Jim was a tireless worker and a fine scientist with a keen physical intuition; his death is a great loss.

3.2 Instrumentation

3.2.1 Multi-channel Photopolarimeters

Magalhaes and his colleagues at the Instituto Astronomico e Geofisico Universidade de Sao Paulo have developed a five-channel polarimeter. The design is similar to that pioneered by Piirola (see p. 735 of the book by Coyne *et al*.). A double calcite block placed just in front of the focal plane and a high speed chopper allow the detector to "see" the e and o beams alternately (46.034.110). Piirola has continued to use his UBVRI multi-channel polarimeter for extensive studies of AM Her type objects and other variable stars. New instruments have also been developed in India and in China.

Bailey and Hough (Hatfield Polytechnic, UK and the Anglo-Australian Telescope) have developed and used a six-channel polarimeter with the unique ability to operate simultaneously in the visible and near-infrared. Two separate beams about 80 arc seconds apart on the sky provide light to the IR and optical detectors with each alternately observing the source and sky background. The instrument separates the standard bands as five optical channels (U,B,V,R,I) and one infrared channel capable of working at either J, H, or K; an InSb photovoltaic detector is used for the near infrared bands. This instrument uses superachromatic half- or quarter-wave plates (made by Bernard Halle, Berlin) which although designed for 0.3 to 1.1 micron still provide efficient polarization modulation throughout the near infrared; the measured efficiency in the K band at 2.2 microns is 87% (see Coyne *et al*. 1990).

The 12-channel photometer-polarimeter known as the "Multi-Purpose Fotometer", or MPF, developed by Tinbergen for the 1-m Jacobus Kapteyn Telescope on La Palma is in full operation (a Users Manual is available from the Royal Greenwich Observatory or La Palma Observatory).

A computer-controlled near-infrared polarimeter featuring a new type of static stress-induced birefringent modulator is described by West *et al*. (46.034.049). Many single-channel or two-channel polarimeters using either rapidly rotating waveplates, electro-optic Pockels cells or photo-elastic modulators are in routine use at many obervatories.

3.2.2 Spectropolarimeters

Several spectropolarimeters now exist which use either CCDs or image photon counting systems. Miller (46.034.079) has developed a CCD-based spectropolarimeter which he has used extensively for the study of active galactic nuclei and quasars. Bailey developed a CCD based spectropolarimeter for the AAT and Tinbergen has recently commissioned a polarimeter module for the ISIS spetrograph on the 4.2-m William Herschel Telescope. This spectrometer provides two detector systems, a CCD and an IPCS. A number of other CCD-based imaging polarimeters are already in use.

3.2.3 Infrared Imaging Polarimeters

Polarimetry of optically invisible infrared nebulae has become possible with the advent of array detectors for the infrared. These detectors do not use the charge-coupling principle but nevertheless provide simultaneous two-dimensional area coverage with very high efficiency (see, for example, McLean [46.013.090, 49.034.088]). Aspin and McLean at the UK Infrared Telescope (UKIRT) have demonstrated near-infrared imaging polarimetry for many applications. Polarimetry at a wavelength of 12 microns has also been achieved successfully by Smith, Aitken, Roche, Gezari and McCaughrean using an array camera developed by Gezari at Goddard SFC.

3.3 Novel Applications

The range of applications of polarimetry is too great to review here. Many applications have been both novel and challenging. Here we mention the following: Extensive multi-colour photometry and polarimetry of AM Her-type objects by many workers including Bailey, Piirola, Schmidt and others has played a major role in the study of these systems. Bastien and his colleagues have made a substantial contribution to the study of T Tauri objects. Dolan has applied the Brown-McLean-Emslie theory to derive orbital inclinations from polarization variations in X-ray sources and has predicted a polarization signature associated with a black hole due to gravitational lensing. Moffat has developed the same theory for the study of Wolf-Rayet binaries. Tinbergen has made the first detailed polarization measurements of the 22 degree ice-halo in terrestrial clouds as a function of scattering angle and at seven wavelengths simultaneously. He concludes that the technique is a powerful tool for the detection of birefringent crystals. Aspin and colleagues have obtained high-resolution imaging polarimetry of proto-planetary nebulae and star forming regions using a near-infrared camera. Finally, Clarke has used a specially designed polarimeter to achieve exceptionally high precision observations of the solar disk. At a level of about 1 part in 10^5 he may have established that the Sun is a variable polarized star!

3.4 Polarimetric Standards

Many groups have contributed observations to the study of both unpolarized and highly polarized stars in the search for "standards." Koch has circulated a list (November 15, 1989) of nominal polarization standards which he has characterised more carefully. Anyone who is interested in this list should contact Bob directly at the University of Pennsylvania.

I.S. McLean
President of the Commission

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