ADVANCES IN PHOTOELECTRIC PHOTOMETRY

VOL. 1

Robert C. Wolpert
Russell M. Genet

Editors

Jill Wolpert

Assistant Editor

Published by

The

FAIRBORN OBSERVATORY

LC No. 82-084767

ISBN 0-911351-01-9

Published in the U.S.A.
by the Fairborn Observatory
1247 Folk Road
Fairborn, Ohio 45324

LC No. 82-084767

ISBN 0-911351-01-9

Printed by BookMasters
830 Claremont Avenue
Ashland, Ohio 44805 U.S.A.

CONTENTS

FOREWORD

This promises to be an interesting and valuable book. It is difficult to describe exactly what the scope is, but let me try. The editors explained to me that, although much about the various activities in this exciting field of astronomical photoelectric photometry are covered in the quarterly I.A.P.P.P. Communications, papers in that publication are necessarily limited in length. They felt, therefore, a need to have certain topics in a book format where each would be given a full chapter. To this I would add the following. Whereas three books have appeared recently (Photoelectric Photometry of Variable Stars, Astronomical Photometry, and Solar System Photoelectric Photometry) to provide the background and the fundamentals, the field is so advanced and is continuing to advance so rapidly that it deserves treatment at a more sophisticated level for the really serious.

Although the book will succeed in providing real substance in the how-to department, I hope it will be equally successful in inspiring readers to embark on photoelectric photometry and inspiring those already underway to continue at a higher level of expertise and with more fervor. My own chapter, which I hope everyone will read, has a message. Please do use your photoelectric equipment, whatever its level of sophistication, to do some real science. I made the statement that, if you are just playing rather than doing real science, you are wasting your investment in telescope, equipment, money, time and effort. Actually that comparison is not fair. Active involvement in real science *is* one of the best games in town, and the satisfaction you feel making a scientific accomplishment or discovery can be one of life's greatest joys.

Reading the section having to do with observations, I was struck by the following. Small-observatory photometrists can do much of what professionals at large observatories can. Moreover, in a number of respects, they can do some things better. This is true because of the convenient year-around access of the backyard or campus telescope, the power of the coast-to-coast or world-wide network of observatories focussed on certain projects like the epsilon Aurigae campaign, and the fact that there still are not enough astronomers (professional or amateur) for all the interesting objects which need observing.

Reading the section on equipment I was struck by the following. Most of the advances described have been accomplished by people who are not the traditional professional astronomer. It seems the typical amateur astronomer is a professional in some other field like computers, electrical engineering, or optics. Just as a professional astronomer subscribes to the I.A.P.P.P. Communications to learn as well as to contribute, I suspect professionals will go to this book to read about recent significant advances in photoelectric equipment and techniques not described elsewhere.

Let me conclude with a few remarks pertaining to the last section, on the observatories themselves. First, whenever actual photoelectric observatories are described, it is inspirational to see proof that it really can be done. Usually one individual is responsible and path followed has been unique. Second, the level of sophistication can be astounding. I do hope, however, that those observatories realize their potential by devoting some time to observing; sadly, it can happen that some observatories become involved in an infinite process of testing, refining, improving, expanding, and enlarging - to the exclusion of anything related to astronomy. Third, it is gratifying to see small-telescope photoelectric photometry gradually covering the entire Earth: both sides of the Atlantic and even both sides of the Equator. Last, I see the day soon when professional astronomers, unable to find ready access to the telescope time they need for their research, will be coming to those backyard observatories. I hear this has already been done at Robert Fried's Braeside Observatory in Flagstaff, and is planned at Russ Genet's Fairborn Observatory in Ohio. The resulting symbiotic relationship will be a benchmark in the development of astronomy.

DOUGLAS S. HALL

Dyer Observatory
Vanderbilt University
Nashville, Tennessee 37235

1

INTRODUCTION

ROBERT C. WOLPERT

Belmont Observatory
144 Neptune Avenue
North Babylon, New York 11704

RUSSELL M. GENET

Fairborn Observatory
1247 Folk Road
Fairborn, Ohio 45324

Astronomical photoelectric photometry had its beginnings in the late 1800's, and for its first 50 years it was practiced only by Joel Stebbins, his followers, and a few others scattered about. The equipment in those days was expensive, heavy, touchy, and generally difficult to operate. Immediately after World War II, Gerald E. Kron introduced the use of the photomultiplier tube to astronomical photometry, and within 10 years its use was widespread amoung professional observatories.

By the mid 1950's, Gerald Kron had taught John Ruiz, an AAVSO member and amateur astronomer, the technique of photomultiplier photometry. In the 1960's a group of amateurs started photometry in New Zealand, and Douglas S. Hall started his work on eclipsing binary stars with the support of a number of smaller observatories. While the number of small observatories equipped for photometry remained few throughout the 1960's and 1970's - perhaps less than two dozen - there were three publications of general interest to the small-observatory photometrist that deserve special note. The first was the AAVSO Photoelectric Photometry Handbook, first published in 1955. While never larger than a couple of dozen pages, it contained the essential information. In 1963, the book Photoelectric Astronomy for Amateurs, edited by Frank B. Wood, was published, and it was and remains the guide to an entire generation of small-observatory photometrists. In 1975, the intrepid New Zealanders held the first symposium devoted to small observatory photometry. The proceedings of this symposium, published in a special issue of Southern Stars, remains a classic well worth reading to this day.

However, in spite of the photomultiplier tube and the fine publications mentioned, only the barest handful of small college and amateur observatories practiced photoelectric photometry until about 1980. Between 1980 and 1983 the number of small observatories equipped for photoelectric measurements has increased by about an order of magnitude, and the growth remains brisk. More than anything else, this growth was made possible by the electronic revolution which made the equipment available commercially at low cost. No longer did one have to either have a fortune or be an electronics wizard. The number of small observatory photometrists became large enough to support a journal, the IAPPP Communications; a couple of books, Photoelectric Photometry of Variable Stars, by D.S. Hall and R.M. Genet, and Astronomical Photometry, by A.A. Henden and R.H. Kaitchuck; and the manufacture of several new commercial photometers by THORN EMI Gencom Inc., Optec Inc., and Hopkins Phoenix Observatory.

This recent "flowering" of small observatory photometrists has produced an increased volume of material that is deserving of publication. We continue to feel quite strongly that observational results should be published in the established journals such as the International Bulletin of Variable Stars (I.B.V.S.), and similar professional journals. Non-observational papers such as requests for observations, descriptions of new equipment, etc., are appropriate to the IAPPP Communications and other journals. However, a small niche remained unfilled for articles too long for most journals, and too specialized for most books. It is our intent to try to fill this small niche. In trying to do so, this is really an experiment. We do not know in advance if there are enough interested small-observatory photometrists out there to buy enough books to pay the printing costs. However, we felt that the time had come to conduct such an experiment. We are most thankful to the many photometrists around the world who had sufficient faith to order this book in advance. We are of course particularly grateful to the authors of the various chapters. This is their book and their story. If the experiment is successful, it will have to be tried again - perhaps as soon as next year, and the editors are ready to have another go at it.

In planning this book and inviting the various contributions, we kept three broad areas in mind: (1) observational, (2) equipment, and (3) observatories. The remainder of this book is divided into sections following these three broad areas. Each of these sections and their contributors and contents are introduced below.

Advances in Observational Photoelectric Photometry

The small-observatory photometrist is first and foremost an observationalist gathering accurate, and hopefully scientifically useful data. If this data is not gathered and published in professional and accessible scientific literature, than all other efforts are to no avail, for we are talking about serious scientific research - not a hobby or some other activity that is an end in itself. This section emphasizes observational programs that are of current scientific interest and well-suited to the equipment available to the smaller observatory.

The first chapter in this section, "The Contribution of Small Telescopes", by Major Steven Shervais, establishes two very important points. They are: (1) that small telescopes equipped for photoelectric photometry produce results that have been published in some quanity in a leading astronomical journal, and (2) that photoelectric photometry is the technique used in the vast majority of papers published in the professional astronomical literature where the observations were made with small optical telescopes. This analysis appears first in this book because it convinces us that serious astronomy *can* be accomplished at a small observatory, which is the underlying basis for all of the remainding chapters.

The next three chapters all concern variable star observing programs in which the variations in amplitude are so small that visual estimates are out of the question, and therefore photometric measurements are required to provide the needed accuracy. They are also observing programs where only the strength of numbers of small observatories can produce the required coverage.

The RS CVn binary stars, D.S. Hall, and small observatory photometry go together like three peas in a pod! More than anything else, it has been Hall's use of small observatory photometry of RS CVn binaries that has established the serious nature of the contribution that can be made to a current and exciting area of science by the properly equipped backyard astronomer. His Starspot Theory was considered highly speculative, but with the data supplied to him by a couple of dozen small observatories, he was able to put this theory on a solid footing, and it is now widely accepted. It was fortuitous that there were a number of rather bright RS CVn binaries, that their amplitude of variation was too small for visual observers to handle but comfortably large for photometrists, and that their periods (typically a few weeks) were too long to be handled in any depth at the major observatories. There was however, nothing fortuitous in the determined way in which Hall and his band of photometrists have kept at these stars year after year. New and often bright RS CVn binaries are always being added to the list, and the true nature of starspot migrations is just beginning to be worked out. A more exciting or successful program is hard to imagine, and it is described in Hall's chapter, "What You Can Do?".

John R. Percy is an indefatigable photoelectric observer of microvariable stars. Along with M. Breger and a few others he has established the basic nature of the various types of stars that pulsate just a few hundredths of a magnitude. While there is no question that these are difficult objects appropriate only for the careful and experienced photometrists, their observation is of considerable importance, and the techniques required to measure these stars are described in his chapter, "Microvariables".

It has been known for several years that B-type stars with emission lines (Be stars) were often variable. They have received increasing attention over the past few years, and the International Astronomical Union (IAU) recently requested an observing campaign on these stars. P. Harmanec heads up this campaign which he explains in some detail in his chapter, "Photoelectric Photometry of Be Stars".

What star is very bright, eclipses every 27 years, and has the theorists completely baffled? It is, of course, Epsilon Aurigae. The hopes are high that this time the code will be broken, and the small-observatory photometrists all over the world are cooperating to provide the data needed to decipher the behavior of this strange object. Jeff Hopkins describes this campaign briefly in his chapter.

The major observatories tend to be situated atop mountains in the best of the World's observing locations. More often than not, the small observatory must struggle with less than ideal observing conditions - low altitudes, city light pollution, and local weather conditions which permit few photometric nights. J.D. Fernie shows that these "underprivileged" observatories can still produce results of consistently high accuracy if appropriate techniques are followed. Through his years of experience has come the important realization that photometry done at poor photometric locations should not be handled in the same fashion as mountaintop photometry. He describes his techniques in his chapter titled, "Photometry Amoung the Climatically Underprivileged".

Advances in Photoelectric Photometry Equipment

In many respects, the problems at small observatories are unique. Low cost and weight are very important, and sometimes the overriding factors in choosing equipment. Many professional astronomers have, in the past, considered instrumentation as a "technician" problem, and some of the astronomical journals have a policy of never publishing instrumentation papers. A more positive attitude toward instrumentation is needed and is usually exhibited (mostly out of necessity!) at the small observatory. While individually each small observatory may not have much money to spend on equipment, collectively there is a significant market potential. Active cooperation between photometrists and commercial manufacturers has resulted in high quality, low cost commercial photometers that have spurred the revolution in small-observatory photometry. Although photometers can now be readily purchased, instrumentation development remains an exciting and vital area of research for the smaller observatory.

N. Walker, of the Royal Greenwich Observatory, has mounted a direct attack on the problem of non-photometric nights with a four-channel, fiber-optic photometer. By rapidly chopping between variable and comparison stars and their backgrounds, he is able to achieve amazing millimagnitude accuracies under the most extraordinary conditions. He describes his system in detail in his chapter, "A Fiber-optic Four Channel Photometer".

Photometry requires more than just a photometer - it requires a complete and intergrated system. As might be expected, JPL scientist R. Stanton has taken a carefully thought out and executed systems approach to his photoelectric equipment and observatory. His chapter should certainly be given special consideration by anyone designing a computer-based photon counting system.

What is the ideal small-observatory photometer? While this question will stir up a spirited debate in any group of photometrists, there can be no denial that what the apartment dweller with a C-8 in his closed would like most is a completely self-contained, battery-operated photometer that will fit in his coat pocket. Only a year or two ago such a photometer seemed like an impossible dream, yet today it is realized in the Optec SSP-3 photometer developed and described by Gerald Pershá and William Sanders in their chapter in this book.

Those who build their own DC amplifiers (and others that just use them) are properly warned that they *must* calibrate the gain steps on these amplifiers if the gain steps are to be changed when going from variable to comparison stars or to the backgrounds. D. L. DuPuy provides the usually missing ingredient for this important operation in his chapter, "A Constant Current Source for Gain Step Calibration".

The next two chapters cover some pioneering work in automating photoelectric observations at smaller observatories. The two efforts are similar in that they both use low-cost microcomputers to control the telescope/photometer systems, and in that both systems use the photometer as an active part of the telescope control system. They differ, however, in that one is a dual-channel system intended for primarily observing short-period stars, while the other is a single-channel system designed to briefly observe many different long-period variables in the same night. The techniques and approaches used in the two systems are quite different and an interesting study in contrast. These chapters, "A Computerized Photoelectric Telescope" and "Small Automated Photoelectric Telescopes", describe the dual-channel system at Fairborn Observatory and the automatic system at the Louis Boyd Observatory respectively.

Advances in Small Photoelectric Photometry Observatories

Just as the small-observatory photometrist must worry about the equipment, so also must he or she worry about all of the details involved in constructing and operating an observatory. Some of the requirements for photometry are different than for other uses of small observatories, and solutions have evolved over time to these common problems. The "observatory" paper never fails to get the attention of the small observatory photometrist. There is a good reason for this - we are all interested in the solutions of others to the same problems we have faced.

Given access to a photomultiplier tube, a chunk of glass or finished mirror, and a few miscellaneous parts, the tradition is that a dedicated amateur astronomer can build a complete observatory and photometer, and use these to make important scientific discoveries, or at least provide good data for some professional's latest program. This tradition is alive and well in the person of R.C. Reisenweber and his Rolling Ridge Observatory. His well-told chapter describes in detail the steps involved in the design and construction of a dedicated photoelectric observatory.

From South Africa comes another chapter in the book of those that built it all themselves - the telescope, observatory, and photometer. L. Pazzi's Nigel Observatory is well thought out, innovative, and nicely executed. As might be expected, it has inspired many other amateur astronomers in South Africa.

The term "small observatory" does not necessarily mean *haywire* or *jury-rigged*. From Sweden comes the description of an observatory so well done that it would be the envy of any big observatory. Stig Ingvarsson has spent over a decade in planning and constructing the T.A.O. Observatory, and in equipping it for photoelectric photometry. An active observer with his EMI STARLIGHT-1 photometer, Ingvarsson is perhaps the northern most observer in the Epsilon Aurigae International Campaign.

The Johnson Observatory is stored in a garage in suburban Maryland, yet in a matter of just a few minutes it is ready for observing with its EMI STARLIGHT-1 photometer and Celestron C-11 telescope. A small printing calculator is used to record the results, and a Radio Shack TRS-80 analyzes the data and plots the resulting light curves. Jay Johnson's innovative attention to detail for his special but not unusual situation will inspire others similarily situated.

From England comes the story of one of our favorite observatories. It has been a special pleasure for us to follow the planning and construction of this observatory almost from the beginning, and to see the influence of its builder, Richard Miles, spread amoungst amateur astronomers in England. This is a nicely constructed observatory which blends into the English countryside in a pleasing manner. In his chapter, "Mouldsworth Observatory", Miles also describes the latest situation regarding amateur photoelectric photometry in England.

The book closes with a brief description of the Lines Observatory. Richard and Helen Lines have built one of the nicest observatories in Arizona, and since they began to make photoelectric observations, the steady stream of high-quality data has been the delight of a number of professional astronomers. The Lines' are the discoverers of a very bright and unusual eclipsing binary star.

2

The Contribution Of Small Telescopes

STEPHEN SHERVAIS, JR.

Headquarters
United States Air Force
Bolling Air Force Base
Washington, D.C. 20332

I. INTRODUCTION

Over the past few years there has been an apparent increase in the number of amateur and student astronomers with the interest, ability, and equipment necessary to make meaningful contributions to our knowledge of the stars. Superficial evidence for this increase includes the growth of organizations such as the AAVSO and IAPPP, the larger apertures of telescopes offered for sale to the general public, and the publication in popular journals of articles on exotic film processing techniques, and advanced equipment construction. This chapter reports the results of one effort to determine how large a contribution has been and can be made by telescopes suitable for amateur use. Since the overwhelming majority of amateur and undergraduate student telescopes have apertures of 40cm or less, it was decided to examine the contribution which such telescopes are making to the scientific literature, and to define the areas of study where those contributions are being made. A secondary purpose was to define the role of amateurs and undergraduate students in these activities.

Two other recent studies of small telescopes should be mentioned. The first, by Abt (1980), was a review of the cost-effectiveness of Kitt Peak (KPNO) telescopes in terms of publications and subsequent citations. Abt reviewed 445 papers based on work done at KPNO and found that about 16% were reporting data obtained with the 40cm telescopes located there. More recently, Genet (Hall and Genet 1981) looked at five years of the Astronomical Journal (1975 - 1979) and found that about 3% of the 890 papers reviewed were based on telescopes 40cm or smaller. The current study was inspired by Genet's research, and uses the same approach.

II. THE SURVEY

The technique used for this study was a review of 2082 papers appearing in the Astronomical Journal between February 1970 and December 1981. Each paper was classified in accordance with the following definitions:

OBSERVATIONAL - papers based on new data obtained at the telescope by at least of of the authors.

NON-OBSERVATIONAL - theoretical papers and those based only on prior observational results. Examination of the Palomar Observatory Sky Survey plates or further analysis of a previously reported catalog would be included here.

NON-OPTICAL - observational papers involving only the use of radiotelescopes or space-based ultraviolet, X-ray, or Gamma ray detectors.

OPTICAL - observational papers involving any visual, infrared, or ground-based ultraviolet detectors.

LARGE TELESCOPES - optical papers based on observations with telescopes with apertures greater than a nominal 40cm (16 inch). If the telescope size could not be identified, it was normally assumed to be large.

SMALL TELESCOPES - optical papers involving any observations made with telescopes having apertures 40cm or less.

VERY SMALL TELESCOPES - optical papers involving any observations with telescopes having apertures less than 40cm. Telescopes of small aperture which require major support systems (such as a 16cm telescope mounted on a Scout rocket) are considered to be large.

The small telescope papers were then classified by observational technique (spectroscopy, photometry, etc.) and object under study; amateur and undergraduate student supported papers were noted, and (since the author is an amateur primarily interested in photometry) photometric papers were further classified by color system.

III. RESULTS

The survey data are summarized in table 1. A comparison of 1970 - 1971 with 1980 - 1981 (two-year averages were taken to smooth year-to-year variations) shows some interesting trends. The average number of papers published each year rose by a total of 47% during this period; primarily because of the publication of two additional issues per

TABLE I

DATA SOURCE OF PAPERS APPEARING IN THE ASTRONOMICAL JOURNAL 1970-1981

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	TOTAL
TOTAL PAPERS	136	160	127	151	181	136	149	160	208	237	213	224	2082
NON-OBSERVATIONAL	42	51	28	43	48	47	40	75	50	75	52	54	605
OBSERVATIONAL	94	109	99	108	133	89	109	85	158	162	161	170	1477
NON-OPTICAL	29	20	28	31	40	24	26	28	57	36	50	58	427
OPTICAL	65	89	71	77	93	65	83	57	101	126	111	112	1050
LARGE APERTURE (greater than 40cm)	49	63	52	64	76	57	71	40	91	120	101	103	887
SMALL APERTURE (40cm or less)	16	26	19	13	17	8	12	17	10	6	10	9	163
=40cm	11	18	17	11	15	6	8	13	3	4	7	4	117
<40cm	5	8	2	2	2	2	4	4	7	2	3	5	46

year starting in 1974. Within this growing body of publications the proportion of papers reporting non-optical observations increased from 16% to 25% of the total, in response to the new data available form space-based systems. On the other hand, the contribution of optical systems to the total remained steady at about 50%.

Of more direct concern to the topic of this chapter, the proportion of papers based on observations with small telescopes declined throughout most of the period surveyed. The trend is portrayed in Figure 1 on the following page. The decline may now have ended, however, since the trend line has leveled off at about 4% during 1978 - 1981. (To confirm that the decline is real, and not just the result of changing editorial preference at the Astronomical Journal, two years of the Publications of the Astronomical Society of the Pacific were checked; the proportion of papers based on small telescope observations declined from 11% of the total in 1970 to 7% of the total in 1980.) The contribution of very small telescopes moved in much the same manner as the larger category, declining fron 4% of the total in 1970-1971 to 2% in 1980-1981. When compared just with small telescopes, rather than with all papers, however, the proportion of papers supported by very small telescopes has actually increased, from 21% small telescope papers in 1970-1975 to 39% in 1976-1981. At least part of this growth appears due to the increase of amateur/student supported papers. No amateur/student supported papers were noted in 1970-1975, while 1976-1981 saw seven papers identifiable as having been produced with the aid of amateur or undergraduate student efforts.

Trends in the publication of a given category of paper in a given journal are subject to a number of influences, not all of them obvious. Some possible influences include changes in editorial preference, or in the format or publication rate of the journal, and competition for space from papers in other categories. At the same time, changes in these factors at other journals may cause a shift in the publication rates independent of the situation at the journal in question.

The most obvious influences on publication trends in the AJ include the increase in papers based on data from space-based systems, and the change in publication rate which ocurred in 1974. Changes at other journals which may have influenced the trends at the AJ include the change in format of the PASP (from a page size of 14cm x 22cm prior to 1971 to a 20cm x 22cm page from 1971 to the present), and the shift of many semi-technical articles to Mercury starting in 1972. The ApJ eliminated its "Notes" section in 1971, causing a drop in the space available for the publication of shorter papers. The implication of these developments is that a thorough understanding of trends in the contribution made by small telescopes in this country can only be gained by looking at publishing trends in all three major American journals.

IV. TELESCOPES AND TOPICS

The majority of the small telescopes used to collect data for these papers were of 40cm aperture; 62% of all small telescopes reported were this size (Figure 2). The next most numerous aperture was 30cm (11%), while very small telescopes overall made up

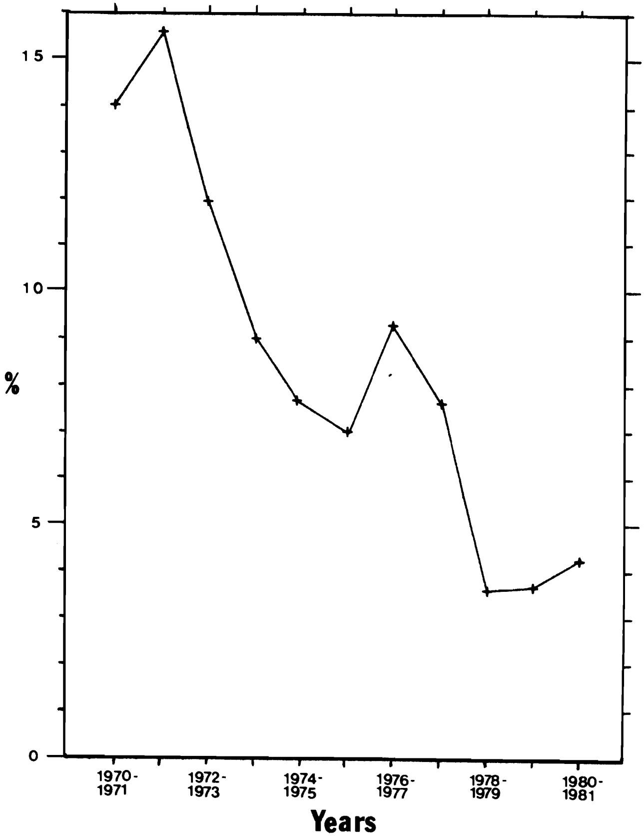


Fig. 1. Small telescope supported papers as a percentage of total papers, <u>Astronomical Journal</u>, 1970-1981, two-year running average.

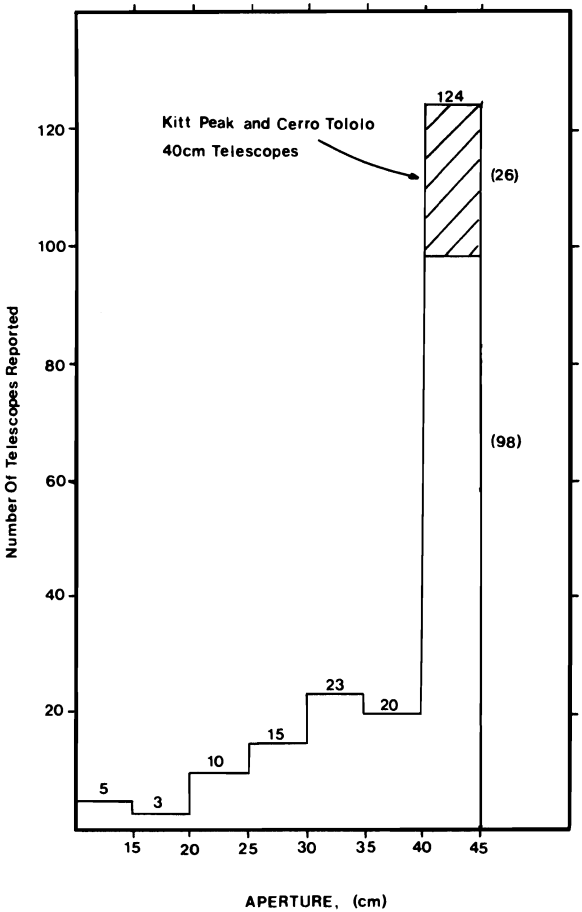


Fig. 2. Distribution of telescope apertures (40cm or less) reported in papers published in the Astronomical Journal, 1970 - 1981.

38% of the total. It is interesting to note that the 40cm telescopes at Kitt Peak and Cerro Tololo make up 13% of all the small telescopes reported, and 21% of the 40cm group. It would seem that these instruments were carrying a disproportionate share of the observing load, and (regarding those at KPNO) it is ironic that the most prolific 40cm telescopes have had their operations curtailed for lack of funds.

Small telescopes have contributed to all areas of optical astronomy, from determining the light curves of asteroids to tracing the spiral arms of the Milky Way. Very small telescopes have had a more narrow employment which has concentrated on light curves of variable stars. Twenty-seven of the 46 papers supported by telescopes less than 40cm in aperture were in this category. Of the 27 papers, ten were on eclipsing binaries, seven on RS CVn variables, four on magnetic stars, and six on other intrinsic variables. Of the 19 papers not dealing with variable stars, seven were studies of comet and asteroid orbits, structure, or composition; four papers reported occultation observations (three asteroid, one lunar); and eight were on such diverse topics as full disc lunar photometry (two papers), meteor studies (three), solar eclipse observations, Milky Way surface photometry, and equipment test (one each).

Within the set of papers listed above, amateur papers concentrated on RS CVn variables (five papers) and occultations (two papers). Two undergraduate student papers on eclipsing binaries were not counted because they were prepared using data collected with 40cm telescopes. Table II lists all papers reporting amateur/student support.

Amateur papers did not deal with any topics requiring spectroscopic observations, all-sky photometry, photographic photometry, or astrometric mensuration. In part, this is an aperture problem. Spectrographic work or all-sky photometry were done only with telescopes 40cm or greater, even by professionals. The other part of the problem is economic. Amateurs would probably be able to produce more data with very small telescopes if only they could afford to purchase, or had access to relatively expensive equipment such as measuring engines or microdensitometers.

Finally, 140 papers reporting small telescope photometric work were broken down by color system. Seventy percent of the papers used the UBV system or its extensions into the rest of the alphabet, and 13% used the narrow-band ubvy system. Included in the combined 83% were 10% of the total papers which used Hβ filters. Other color systems (primarily DDO and specialized narrow-band) made up the remaining 16% of the reported papers. Amateur and student work was all done in one or more of the UBV colors, although some of their papers included observations made in other colors with large telescopes.

V. CONCLUSIONS

The data surveyed for this chapter show that small (even very small) telescopes, in the hands of careful amateurs and undergraduate students who are properly guided by professionals in the field, can make significant contributions to our knowledge of the stars.

TABLE II

AMATEUR AND UNDERGRADUATE STUDENT-SUPPORTED PAPERS APPEARING IN THE ASTRONOMICAL JOURNAL 1970-1981

VOLUME/ PAGE	PRINCIPAL AUTHOR*	TITLE
81/665	Grauer, A.D.	Period Study and UBV Light Curve of MN Cas**
82/47	Bopp, B.W.	Photometry of the Radio Variable HR 1099
82/740	Grauer, A.D.	Period Study and UBV Light Curve of TV Cas**
83/176	Landis, H.	1976-1977 Photometry of UX Ari, HR 1099, and λ And
83/1510	Bartolini, C.	1977-1978 Photometry of V711 Tau (HR 1099): Before the Radio Outburst
83/1514	Chambliss, C.	1978 Photometry of V711 Tau (HR1099): During the Radio Outburst
84/261	Wasserman, L.	The Diamater of Pallas
85/744	Burke, E.	Photometry of HR 5110 Before, During, and After the Radio Outburst in June, 1979
86/306	Mills, R.L.	The Diameter of Juno From Its Occultation of AG+0^{0}1022

* All papers had multiple authors. Only the one listed first on the title page is shown here.

** Undergraduate student support indicated.

Although there has been a relative decline in the use of small telescopes, the participation by amateurs has shown a marked increase, and there are still a number of topics in which amateur participation has yet to realize its full potential.

In all of this we should not forget the large telescopes. In many, perhaps most, of the small telescope papers discussed here, the small telescope was not the only system collecting data. The study of faint stars, or the use of narrow bandpasses, requires large telescopes; and much of the small telescope data is used to supplement those studies.

Likewise, the role of the professional astronomer has been neglected in this chapter. It is the professionals who suggest topics, guide the amateur around observational pitfalls, and make sense of the resulting data. Perhaps the highest praise is due to them because of their willingness to credit amateur authors on an equal basis with themselves. If the degree of non-professional participation has been under-reported in this chapter, it is for the laudable reason that it is impossible to identify amateur or student authors unless the names of the individuals (or their observatories) are known. Astronomy is one of the few disciplines where this is true, and it is the professionals who allow this happy state of affairs to exist.

The author would like to acknowledge the kind assistance of the library staff at the U.S. Naval Observatory, Washington, D.C. in the research for this chapter.

REFERENCES

Abt, H.A. (1980) P.A.S.P. 92, 249.

Hall, D.S., and Genet, R.M., Photoelectric Photometry of Variable Stars (IAPPP) pp. 1.3 to 1.5.

3

WHAT CAN YOU DO?

DOUGLAS S. HALL

Dyer Observatory
Vanderbilt University
Nashville, Tennessee 37235

I. INSPIRATION

Now that your telescope is equipped for photoelectric photometry, you should begin obtaining measurements of astronomical objects that will yield scientifically useful results. If you do not, then you will be wasting all the time, effort, and money invested in your observatory, telescope, and equipment. That strong statement is a personal viewpoint which some might not share, arguing that astronomical activity can be rewarding for its sheer enjoyment even though not scientifically useful. I do feel that way, however, and invite you to join the battle against the unknown. It is a group effort involving all mankind and every individual can help move the line forward.

So, what can you do, specifically? In chapters 15 and 16 of the book by Hall and Genet (1982) I explained in detail how to go about selecting a scientifically worthwhile observing program. In that discussion I emphasized that your efforts should be directed against specific well-defined targets, so that your valuable shots would not land in the bushes. At the same time I hesitated to suggest specific observing programs in detail, since the targets are continually moving. The quarterly I.A.P.P.P. Communications are proving useful in pinpointing good targets and updating them on a timely basis. Just a listing of research projects described in recent issues of the I.A.P.P.P. Communications includes (1) discovery of new variable stars, (2) light curves of variable stars such as eclipsing binaries like U Cephei and ε Aurigae, rotating spotted stars like RS Canum Venaticorum and BY Draconis, pulsating stars like RR Lyrae and Mira, novas like Nova Cygni 1975, and B-type emission stars like Pleione, (3) timing minima of eclipsing binaries for the purpose of determining the orbital period or studying variations in the period, (4) determinination of photoelectric magnitudes for sequences of comparison stars used by visual observers when making eye estimates, (5) photometry of comet nuclei, (6) occultations of stars by planets or asteroids, (7) light curves of tumbling asteroids, (8) photometry of the nucleus of bright galaxies like M31, and (9) photometry of sky brightness for the purpose of studying light pollution.

Let me be specific here and describe three astronomical problems which you could tackle immediately with a telescope of modest size. I will confess that all three are personal favorites of mine, with which I have struggled for many years. Nevertheless, all are important, all are unresolved at this time, and all are likely to remain so for years into the future.

II. DISCOVERY OF NEW VARIABLE STARS

There are around a hundred billion stars in our galaxy. A few percent of those, over ten billion, vary in brightness with ranges of at least a few hundredths of a magnitude, which can be detected by photoelectric photometry. According to the Third Edition of the General Catalogue of Variable Stars and its first three Supplements, over 25,000 variable stars are known. It would not be an efficient investment of your time to embark blindly on a project of doubling that number to 50,000. Focusing on the bright stars, however, would be worthwhile. Bright stars are important, not just because they are accessible to small telescopes, but because they will be the ones for which other types of observations (with spectrographs and polarimeters, with X-ray and far-ultraviolet satellites, with infrared and radio telescopes) will yield the most useful results also. Stars examined from all angles will be the most completely understood and hence the most valuable scientifically. Of the 9110 stars in the Yale Bright Star Catalogue there are certainly variables yet to be discovered. The 1964 Edition listed 250 variables as known and the 1982 Edition, only 18 years laters, listed 610! Moreover, Hoffleit (1979) drew attention to 1261 stars in that catalogue already flagged as suspected variables. Just since 1972 I myself (working sometimes in collaboration with other astronomers, both amateur and professional) have discovered over two dozen new variables, roughly half of them in the Yale Bright Star Catalogue. So the field is far from completely harvested.

There probably are surprises waiting for us. Although we will encounter more examples of familiar objects, we may find something completely new. Just since the 1960's, astronomers have discovered a handful of brand new categories of variable stars. The ZZ Ceti-type variables are pulsating white dwarf stars, planet-sized stars that oscillate with periods measured in minutes. The pulsars are rapidly rotating neutron stars, asteroid-sized stars which vary in light with periods measured in seconds or tenths of a second. The BY Draconis-type variables (discussed in the next section) are cool stars which vary as large dark regions on their surface rotate into and out of view. Certain types of peculiar galaxies (the Seyfert galaxies, the BL Lacertae-type objects or Lacertids, and the quasars) vary in brightness irregularly on a variety of timescales. The mechanism still is not understood but probably is related to a giant million-solar-mass black hole presumed to be buried in the heart of the galactic nucleus.

It is interesting to note that Hercules X-1, the first X-ray source discovered in the constellation Hercules, was known already 25 years ago as the irregular variable star HZ Herculis. No one then suspected it was a binary system containing an X-ray-emitting pulsar; in fact, it was not realized until 1967 that neutron stars even existed. It is also interesting to note that Cygnus X-1, the first X-ray source discovered in the constellation Cygnus, corresponds to the bright (V = 8.9) star HDE 226868, which could have been discovered as a variable star decades ago by an amateur with simple photoelectric equipment on a 10-inch or 12-inch telescope. As existing light curves now show, it varies in brightness by about 5%, with a period of 5.6 days. Only recently have we learned that this apparently ordinary star is a binary system containing an X-ray-emitting black hole, the first black hole astronomers discovered. Thus, history teaches us that, among the variable stars, surprises are surely waiting to be found.

III. STARSPOTS

I am very excited about starspots. It seems perhaps I have written about starspots too much: in Sky and Telescope (Zeilik et al. 1979), in Section G of Chapter 16 in my book with Russ (Hall and Genet 1982), in Astronomy (Hall 1983), and in numerous more technical articles. But it is a fact that starspots are new on the scene: you will not find them even mentioned in a typical introductory-level astronomy text or popular-level astronomy book. Yet starspots represent an outstanding phenomenon, potentially of profound significance, and still not understood by the best astrophysicists. When an important new phenomenon is discovered and cannot be explained by existing theory, the first step is for observers to gather careful observations which will serve to define exactly what the phenomenon is and hence exactly what needs to be explained. In this context it is fortunate that amateurs with telescopes as small as 8-inches are able to make those observations. Nature helped by putting starspots on bright stars.

In the book by Hall and Genet (1982) and in various articles in the I.A.P.P.P. Communications I have outlined a specific observing program for photoelectric photometry with small telescopes designed to be most useful in getting the best, scientifically meaningful observations. Starspots occur on one star in binary systems of the RS Canum Venaticorum type and the W Ursae Majoris type. They occur in the BY Draconis-type variables, which may be either single or binary. They occur in the newly discovered FK Comae-type variables, which might be single cool giant stars with a pair of close binary stars rotating in the core. And they may occur in the irregular T Tauri variable stars, discussed later in this section. Of these, the RS CVn binaries are the brightest, with over a dozen occurring in the Yale Bright Star Catalogue.

Let me describe the phenomenon itself briefly. We have cool stars whose surfaces are mottled unevenly by large groups of dark spots covering up to 40% of one hemisphere. They appear to us as variable stars because the brightness decreases and increases as the spot group rotates into and out of view. From here on, however, only questions follow.

1. How big can the spot groups get? The light variation (the so-called photometric wave) is greatest when the spot group is large, much cooler than the surrounding photosphere, and confined to just one hemisphere. The largest light variation discovered so far is about 0.4 magnitudes, which implies a group covering about 40% of one hemisphere. Recall that the sun, even at sunspot maximum, has only about 0.5% of its surface covered with spots.

2. How long do they last? Spot groups on the sun break up and fade away after just a month or two. Spot groups on several RS CVn binaries have been observed to exist continuously for decades. The record seems to be the 4th magnitude star λ Andromedae (Boyd et al. 1983). Its variability was discovered on the basis of photoelectric photometry begun in 1933 and the variability has been observed to persist ever since then. Exactly a half century has elapsed since 1933 but one can suppose that the long-lived spot group probably was in existence even before then. Spot groups on some other stars have been observed to last for a few decades before dying away and being replaced by others. In other stars a large spot group seems to have trouble maintaining its identity even for a year. The question of longevity is not at all understood, either observationally or theoretically.

3. How fast can they change? If the size and/or the temperature and/or the density

of spots within the group changes, then the amplitude or the shape of the wave will change. Light curves of several RS CVn variables have been seen to change markedly within only one or two months, implying that the spot group becomes darker and/or larger on that same time scale. This aspect of the phenomenon also is not at all understood.

4. Are there spot cycles? Just as numbers of spots on the sun wax and wane every 11 years, we can ask if they do so on heavily spotted stars also. To date we simply do not know. The approach has been to see if the amplitude of the wave varies cyclically, but there are two tricky problems. First, if a second spot group forms on the opposite hemisphere, that will decrease the wave's amplitude even though the total area covered with spots has increased, thereby complicating the interpretation. Second, there is not even one convincing example of a clearly repetetive cycle. It may be that these huge spot groups (which can cover a hundred times more surface area than those on the sun do) follow laws of their own and there simply is no counterpart to the 11-year sunspot cycle. We must wait and see what the answer is. Similarly we can ask if there is a counterpart to the Maunder minimum, that 70-year interval between approximately 1645 and 1715 when virtually no spots were seen on the sun.

5. What about sector structure? On the sun there is weak evidence that spot groups have a statistical tendency to form within two 90-degree regions of solar longitude and not within the two 90-degree regions in between. Does the same phenomenon occur, perhaps more clearly, in heavily spotted stars? Some stars have always, at least as long as we have observed them, had two large spot groups, on opposite hemispheres. These include σ Geminorum, HD 185151, and HD 136905. The light curves of others have proven two such groups exist at least occasionally. These include λ And, V711 Tauri, II Pegasi, and RS CVn itself. Sector structure, even if we succeed in establishing its existence on these stars, is a phenomenon which the theoreticians have not even begun to explain.

6. Can we use light curves to construct maps of starspot regions? The answer is, frankly, no. It has been proven mathematically that in principle an infinite number of different spot patterns can produce the same light curve. Thus it is impossible to analyze a given light curve in such a way as to deduce the <u>one</u> spot pattern which is the correct one for that star. A new technique, being developed by Steven S. Vogt and Francis K. Fekel, involves using radial velocities derived from high dispersion spectrograms to deduce spot patterns. That technique has similar problems with uniqueness, but it is likely that the two techniques, photometric and spectroscopic, used in concert can succeed in constructing unambiguous starspot maps. The situation is quite fluid now and a satisfactory solution to the problem lies in the future.

7. What can we learn from the <u>average</u> brightness of these stars, which also is variable? A fundamental theoretical question, not yet answered, is the following: when a dark spot region develops, where does the diminished light go? It might creep out immediately around the periphery of the spots. It might be stored in deeper layers of the star, maybe to come out later, maybe not. It might cause the radius of the star to change. Or it might be some combination of all three possibilities. This so-called "missing flux problem" is not yet understood even for the sun. We can hope that the heavily spotted stars, in which the phenomenon is occurring to a much more extreme degree, can be of more help. The

question is, however, completely unanswered at the present time.

8. Can we figure out the synchronization problem? Almost all of the spotted stars which occur in binaries rotate very nearly synchronously. That means the star rotates once as it orbits its companion star once. One problem is understanding why they never rotate exactly synchronously. The two periods (photometric and orbital) always differ by a percent or so. Some astronomers note that different latitudes of a star probably rotate at slightly different rates, as they do on the sun, and speculate that spots occurring at different latitudes therefore would probably rotate at slightly different rates, but there are no calculations to back up this supposition. Another problem is that, in some binary systems, the rotation is not at all synchronous. The three outstanding examples are λ And, AY Ceti, and BY Dra. In one case (BY Dra) the explanation is probably related to the large orbital eccentricity ($e = 0.35$), but in the other two the orbits are not far from circular ($e = 0.0$ for λ And and $e = 0.1$ for AY Cet), so orbital eccentricity cannot be the entire explanation. Here we see that the study of spots has revealed another problem, perhaps not directly related to spots themselves, but an unsolved problem nevertheless.

9. Are there starspots on stars other than the RS CVn binaries, the W UMa binaries, the BY Dra variables, and the FK Com stars? The most likely and interesting possibility is the T Tauri variables. These are young cool giant or subgiant stars not yet undergoing nuclear fusion in their cores and therefore still contracting towards the main sequence. For a long time they have been known as variable stars, with generally irregular light curves. Most astronomers believe that the light variation is a result of an irregular dusty circumstellar disk or shell still surrounding and rotating around the star. Based on photometry obtained in the 1950's, Hoffmeister (1970) reported discovery of nearly periodic light variations in four T Tauri variables (T Chamaeleontis, RY Lupi, RU Lupi, and AK Scorpii) and suggested that the cause was rotation of an unevenly spotted star. Although astronomers now accept the idea of huge starspot groups on stars like RS CVn, W UMa, BY Dra, and FK Com, the T Tauri variables have not been included. Only very recently has a paper appeared (Rydgren and Vrba 1983) to revive and support Hoffmeister's theory. The question is not yet settled and more hard work is needed before it will be. The T Tau variables are not very bright and we need long uninterrupted photometric runs to establish periodicity, which might be concealed by irregular light variations that occur simultaneously.

IV. BINARIES WITH VARIABLE PERIODS

The time required for the two stars in a binary to revolve around each other is called the orbital period. If the plane of the orbit lies nearly enough in the earth's line of sight, then we see eclipses whenever one star goes behind the other. The most accurate way to determine a binary's orbital period is to observe such eclipses and measure the time elapsed between. This has been done for Algol and β Lyrae, the first two eclipsing binaries discovered, for a couple of centuries. Almost immediately it was discovered that the orbital period of neither one was constant. Variable periods have been found since then in a large number of other eclipsing binaries, a sizable fraction of them, and variable periods still continue to puzzle astronomers.

There are two eclipses per orbital revolution. Primary eclipse, the deeper of the two, occurs whenever the hotter star goes behind the cooler star. Secondary eclipse, the shallower of the two, occurs whenever the cooler star goes behind the hotter one.

Period variations are studied by means of a so-called O-C diagram. We plot, versus time, the observed time of mid eclipse minus the time computed with an ephemeris which assumes a constant period. If the resulting sequence of points, the so-called O-C curve, defines a straight line, then the period is constant. If a straight-line O-C curve slants up or down, that means merely that the period assumed in the ephemeris is too short or long, and can be adjusted accordingly. If the O-C curve actually curves, then the period is variable, with upward curvature indicating an increasing period and downward curvature indicating a decreasing period, If the O-C curve consists of two straight-line segments, of different slope, then the period must have changed abruptly at the moment when the slope suddenly changed.

Three mechanisms are known which can, and do, account for many variable periods. Certain puzzling cases remain, however, which probably will lead us to an as-yet-unknown mechanism. All aspects of the problem are fascinating: the observations themselves which show the periods to vary and the theories used to explain them.

One mechanism is apsidal motion. If an orbit is circular, then secondary eclipses occur midway between successive primary eclipses. If the orbit is eccentric, they do not. If either star has a finite size (which is always so, because no star is a point mass), then the major axis of the orbit (the line of apsides) will rotate slowly in space, with the rotation being faster if the star's radius is large relative to the major axis. The rotating line of apsides causes the uneven primary-vs-secondary spacing to vary with time. Specifically, the O-C curve for primary eclipse will be a sine curve and the O-C curve for secondary eclipse will be another sine curve of equal amplitude but 180 degrees out of phase. The period for one cycle of the sine curve is the apsidal motion period and the amplitude depends on the orbital eccentricity. Apsidal motion has been detected convincingly in several eclipsing binaries, though no more than a dozen or two, because apsidal motion periods are usually very long, sometimes over a century.

A second mechanism is the light travel time effect. If the eclipsing binary belongs to a triple star system, it will orbit the center of mass of the triple system with some longer period. Whenever the eclipsing pair is between the center of mass and the Earth, its light has a shorter distance to travel, will arrive early, and results in negative O-C residuals. Whenever it is on the far side of the center of mass, the result is positive O-C residuals. The O-C curve thus will appear as a sine curve if the long-period orbit is circular or a skewed sine curve if the long-period orbit is eccentric. Notice that both primary and secondary trace out the same O-C curve; there is no 180 degree shift as there is with apsidal motion. The amplitude of the curve measures the size of the long-period orbit: if the O-C residuals range between 10 minutes late and 10 minutes early, for example, then the eclipsing pair is 10 light minutes (about 1.2 astronomical units) from the center of mass.

A third mechanism is mass transfer (from one star to the other) or mass loss (from the binary system). Depending on the details of the mass flow (speed, direction, density, turbulence, etc.) the orbital period will either increase or decrease. One of the most dramatic examples (of a period increase) is β Lyrae. Eclipse timings dating back to 1784 (Klimek and Kreiner 1973) show that, ever since its discovery by Goodricke, the period has been getting longer by about 2/3 second each orbital cycle. The ~12.9-day period is now about 0.04 days longer than it was in 1784. But the O-C curve, which measures the cumulative effect, is most dramatic. If O-C residuals are computed with an ephemeris based on the period β Lyrae had in 1784, then we see eclipses are now occuring three and a half months behind schedule!

What still puzzles astronomers, however, are those binaries whose periods increase <u>and</u> decrease in an irregular manner and those whose periods show one or more <u>abrupt</u> increases or decreases. Algol itself is an eclipsing binary whose period has varied in this way, for centuries, and still is not understood. Söderhjelm (1980) published a comprehensive review of all that is known about Algol, and Mallama (1982) more recently discussed the period variations themselves. Recall that apsidal motion or the light travel time effect can be invoked only if the O-C curve traces out a pattern which is strictly periodic, and apsidal motion further requires primary and secondary eclipses to have O-C curves characteristically 180 degrees out of phase. For several years I have struggled to show that mass transfer and/or mass loss can explain those puzzling irregular back and forth O-C curves (Hall 1975) as well as the cases which indicate monotonic period increases or decreases. But certain predictions implied by my explanations have, frankly, not checked out (Olson et al. 1981). This lack of success prompted Matese and Whitmire (1983) to propose a totally different mechanism. They have hypothesized that one star undergoes changes in its radius (or redistributes the density within its interior) and that the subsequent rebalancing of angular momentum forces the orbital period to change. There is no underlying theory to explain why their hypothesized radius changes might be occurring and not even any proof that they actually are, but Matese and Whitmire may be on the right track nevertheless. I want to draw your attention to two particular eclipsing binaries which may prove crucial in confirming (or denying) the Matese-Whitmire mechanism. The two eclipsing binaries U Ophiuchi and TX Herculis seem to undergo the characteristic irregular back and forth period changes (Herczeg 1980). Neither system contains a star which is overflowing its Roche lobe, so mass transfer cannot reasonably be invoked as a mechanism. Also, the stars in both systems are not cool enough to be convective, so mass loss by a solar-wind-type mechanism (Hall and Kreiner 1980) is not expected. That leaves the Matese-Whitmire mechanism as the only (or the most) likely possibility. There is, however, a chance that their O-C curves <u>are</u> periodic, in which case apsidal motion or the light travel time effect might provide the explanation afterall. The problem is that not enough eclipse timings exist for either system to decide whether the O-C curve's pattern is repetetive or irregular. Additional careful photoelectric eclipse timings over the next several years should decide the matter.

REFERENCES

Boyd, R. W. et al. 1983, Astrophysics and Space Science 90, 197.

Hall, D. S. 1975, Acta Astronomica 25, 1.

Hall, D. S. 1983, Astronomy 11, No. 2, 66.

Hall, D. S. and Genet, R. M. 1982, Photoelectric Photometry of Variable Stars (Dayton: I.A.P.P.P.).

Hall, D. S. and Kreiner, J. M. 1980, Acta Astronomica 30, 387.

Herczeg, T. 1980, I.A.U. Symposium 88, 89.

Hoffleit, D. 1979, J.A.A.V.S.O. 8, 17.

Hoffmeister, C. 1970, Veränderliche Sterne (Leipzig: Johann Ambrosius Barth), p. 41.

Klimek, Z. and Kreiner, J. M. 1973, Acta Astronomica 23, 331.

Mallama, A. D. 1982, J.A.A.V.S.O. 11, 1.

Matese, J. J. and Whitmire, D. P. 1983, Astronomy and Astrophysics 117, L7.

Olson, E. C., Crawford, R. C., Hall, D. S., Louth, H., Markworth, N. L., and Piirola, V. 1981, P.A.S.P. 93, 464.

Rydgren, A. E. and Vrba, F. J., Ap.J. 267, 191.

Söderhjelm, S. 1980, Astronomy and Astrophysics 89, 100.

Zeilik, M., Hall, D. S., Feldman, P. A., and Walter, F. 1979, Sky and Telescope 57, 132.

4

MICROVARIABLES

JOHN R. PERCY

Erindale College
and
David Dunlap Observatory
University of Toronto
Toronto, Canada

I. INTRODUCTION

I shall arbitrarily define microvariables as *variables with brightness ranges (Δm) which are so small (say $0^m.2$ or less) that they can only be studied using photoelectric photometry*. They are of interest for many reasons. First of all, they are numerous: whereas in the Yale Catalogue of Bright Stars (Hoffleit, 1982), there is only a handful of such famous macrovariables as Mira, Cepheid and RR Lyrae stars, there are hundreds, perhaps thousands, of microvariables. All of these are within the reach of small telescopes, but I do not recommend the study of all of these stars by beginners: some are particularly challenging, and their discovery and study require the utmost care. Often the beginning photometrist encounters microvariables quite by accident - in the form of comparison stars which turn out to be slightly variable.

To the professional astronomer such as myself, microvariables are worthy of study because, like other variables, they can provide valuable information about stellar properties and processes. Different classes of microvariables provide information about masses, radii and luminosities, rotation and magnetic fields, starspots, diffusion and convection, pulsational instability, and mass loss.

Microvariables can be divided into certain classes, and these are generally found among certain classes of Stars. Delta Scuti stars, for instance, are found among A5 - F2 stars near the main sequence. Such microvariables can be discovered efficiently through photometric studies of stars of the appropriate class. This approach is *not* very effective in turning up new *classes* of microvariables.

A more unbiased sample of microvariables can be found as a byproduct of the compilation of a photometric catalog. As an example, in F. Rufener's (1976) "Second Catalog of Stars Measured in the Geneva Observatory Photometric System", there is an appendix listing several hundred stars whose magnitude and/or color determinations show undue scatter. Of these stars, 333 which were not previously known to be variable are discussed in more detail in a subsequent paper by Rufener and Bartholdi (1982). This provides one of the most complete and unbiased surveys of microvariability among the bright stars. Donald MacRae's table of "The Brightest Stars" in the annual Observer's Handbook (Bishop, 1982) contains almost complete information on the microvariability of the 286 brightest stars. The Yale Catalogue of Bright Stars (Hoffleit, 1982) contains information about the variability and suspected variability of the 9100 brightest stars. This information is derived from the General Catalogue of Variable Stars and its supplements, and from the Catalogue of Suspected Variables, respectively.

II. THE STUDY OF MICROVARIABLES

I do *not* recommend that you observe microvariables unless you are an experienced and careful "millimag photometrist" who can routinely achieve and *demonstrate* a precision of $\leq 0.^{m}005$ in your observations. Michel Breger (1969), one of the best of the "millimag photometrists", tells how to achieve this: aside from such obvious things as keeping your mechanical, optical, and electronic systems in good working order, and not observing on cloudy nights, you should (i) work differentially, (ii) use *at least* two comparison stars, so that you can demonstrate the constancy of these, and monitor the quality of the night, (iii) observe program *and* comparison stars *frequently*, and for a long enough time to overcome photon statistics, (iv) center the star *carefully* in the diaphragm, so as to illuminate the photocathode consistently, and don't let the star drift away from this position, (v) choose comparison stars which are near the program star, and similar to it in color and magnitude, (vi) if necessary, correct *rigorously* for differential extinction and differential color, (vii) if you are comparing your observations with those made with other telescope-filter-photometer systems, reduce *all* of them *rigorously* to a standard system such as UBV, (viii) for most stars, use a V or a B filter; U filters can be very troublesome.

Some of these instructions are easier to give than to carry out. It is no mean feat, for instance, to find constant comparison stars which satisfy rules (ii) and (v), especially if the program star is very bright.

One comment: the secret of success in studying microvariables is *care* in every aspect of the observing and data reduction process. The automation of these processes is a secondary consideration. In fact, automation can often hide serious flaws in the data. Believe it or not, I still reduce most of my photometric data by hand.

The analysis and interpretation of observations of microvariables is also difficult, especially since many of them are irregular, or multiperiodic, or subject to spurious periods. One should be skeptical of *any* analysis of microvariables (especially one's own).

III. THE CLASSIFICATION OF MICROVARIABLES

The most common classes of microvariables are listed in Table I, and are described below. They include classes of variables which are always microvariable (such as the β Cephei stars) and classes of variables which are sometimes microvariable (such as the classical Cepheids). These classes of microvariables have then been grouped according to the basic mechanism of their variability. Although this is as good a way of grouping them as any, it has some disadvantages: (i) in some classes, the variability may involve two or more mechanisms. The Be stars, for instance, may show both eruptive and pulsational/rotational variability, (ii) in some classes, we are not sure of the basic mechanism of the variability, and (iii) classification or "pigeon-holing" often obscures close relationships between classes.

TABLE I

This table lists the types of variable stars of which at least some members are microvariable. The columns give the types, the approximate number N in the _Yale Catalogue of Bright Stars_, the typical range, period and spectral type, and a few examples.

TYPE	N	TYPICAL PERIOD (d)	TYPICAL RANGE (m)	TYPICAL SPECTRUM	EXAMPLES
A. Eclipsing	50	$0.5-10^4$	any	any	δ Ori, α CrB
VV Cep	5	10^3-10^4	0.1	supergiant	ζ Aur, ε Aur
B. Ellipsoidal	15	1-5	0.05	usually B	α Vir, ψ Ori
C. Rotating					
1. Peculiar A	200	1-10	0.05	Bp, Ap, Fp	α^2 CVn
2. RS CVn	50	1-15	0.1	F-G IV	λ And, σ CrB
3. BY Dra	0	1-10	0.05	K-M V	BY Dra
4. FK Com	?	1-10	0.05	F, G, K	FK Com, ?
D. Pulsating					
1. Cepheid	12	1-8	0.1	F I	α UMi
	12	>40	0.1	F-G Ia	89 Her, ρ Cas
2. δ Sct	200	0.03-0.3	0.05	A5-F2 III-V	β Cas, δ Sct
3. ZZ Cet	0	$10^{-3}-10^{-2}$	0.1	white dwarf	ZZ Cet
4 β Cep	100	0.1-0.3	0.05	B1-B2 III-IV	β Cep, β CMa
5. SARV	200	10-100	0.1	M III	α Tau, β Peg
6. Supergiant	200	10-400	0.05	O-M I	κ Cas, ρ Cas
E. Miscellaneous					
1. Be	200	any	0.1	Be	γ Cas

A. ECLIPSING VARIABLES

In these variables, a decrease in brightness occurs because of a geometrical eclipse of one star by another. Many eclipsing variables have large ranges (Algol and β Lyr, for instance); others are microvariable. Among the 286 brightest stars, several are eclipsing microvariables. Most such microvariables are known, but new ones are occasionally discovered, such as 1 Per (North et al, 1981) and 16 Lac (Jerzykiewicz et al, 1978). The latter star is particularly interesting, and it illustrates the importance of eclipsing variables: it is also a pulsating microvariable of the β Cephei class, and the eclipse allows its mass and radius to be determined. It is one of the only pulsating variables in which a direct mass and radius determination is possible. Photometrists can perform a useful function by searching for possible eclipses in known spectroscopic binary stars. The probability and the time of the eclipse can usually be determined in advance from the spectroscopic observations.

There is also a class of supergiant eclipsing variables known as VV Cephei stars, which includes 31 Cyg, 32 Cyg, ζ Aur, and possibly ε Aur. In these stars, the visual range is often rather small and the period and the eclipse are rather long. These stars are therefore suitable for study using small telescopes equipped with photoelectric photometers. In these and in some other eclipsing variables, there are also small intrinsic variations which must be studied using photoelectric techniques. An international campaign (described in another chapter of this book) has recently been organized to study the eclipse and intrinsic variations in ε Aur.

B. ELLIPSOIDAL VARIABLES

Ellipsoidal variables, like most eclipsing variables, are close binary stars, but in this case the orbit is not seen edge-on, so there are no eclipses. The variability occurs because the stars tidally distort each other into elongated shapes called ellipsoids. As the two ellipsoids revolve around each other, we see different projected areas, and regions of different temperature, so the brightness appears to vary.

The periods of binary stars which are close enough to distort each other are usually less than 5 days, and the spectral types are usually O or B. The total range is typically $0^m.05$, so they *must* be discovered and studied photoelectrically. The light curve has two maxima and two minima in each (spectroscopic) orbital cycle. This is the test for identifying ellipsoidal variables; otherwise, they could be confused with pulsating or rotating variables. Simultaneous analysis of the spectroscopic orbit and the photometric variability leads to an estimate of the mass and radius of the two stars.

The best-known ellipsoidal variables are α Vir (Spica), ψ Ori, o Per, and π^5 Ori. There are about a dozen other ellipsoidal variables in the Yale Catalogue of Bright Stars, including several recently discovered by McCrosky and Whitney (1982).

C. ROTATING VARIABLES

Rotating variables are stars with non-uniformly-bright (patchy) surfaces. As the star rotates, regions of different brightness, color, and other properties pass under the observer's line of sight, and these properties appear to vary with a period which is the rotation period of the star. Since all stars rotate, any star with a patchy surface will be a rotating variable unless the patches are symmetrical about the rotation axis, or unless the axis of rotation points to the observer. The patches are usually caused by the star's magnetic field: either a general magnetic field at some angle to the axis, or a localized magnetic field producing starspots.

The period (P) of a rotating variable is related to the equatorial rotation velocity (V) and the radius of the star (R) by $P = 2\pi R/V$. We view the rotation axis at some arbitrary angle i to the line of sight so, if we express P in days, V in km/s and R in solar radii, then the spectroscopically measurable (by the Doppler effect) component of V is

$$V \sin i = 50.6\ R\ (\sin i)/P$$

This provides a test for rotational variability in a group of stars of similar radius: if V sin i is plotted against P, then the upper envelope of the plot should be a hyperbola with the equation, $V \sin i = 50.6\ (R/P)$. Among the rotating variables, the radius is typically 1 - 10 $R_\odot$, and the rotational velocity is typically 10 - 100 km/s, therefore the period is typically a few days.

As far as we know, rotational variability is confined to stars on or near the main sequence (the region in the Hertzsprung-Russell diagram of stellar luminosity vs temperature where most stars are found). The possibility should not be overlooked, however, that other types of stars show rotational variability as well.

C-1. THE PECULIAR A STARS

The first-known and best-known group of rotating variables are the peculiar A stars. They make up about 20% of all A stars, and together with their relatives the peculiar B and peculiar F stars, they form a sequence of stars of decreasing temperature. Related to the decreasing temperature is a sequence of spectral peculiarities, involving apparant over- and under-abundances of certain chemical elements. Peculiar stars are denoted by a "p" following their spectral type (e.g. Bp, Ap, Fp). Such stars should obviously not be used as comparison stars in photoelectric photometry, nor should any other stars which are prone to microvariability.

The strength of the spectral peculiarities can appear to vary with time in a periodic fashion; hence these stars are sometimes called *spectrum variables*, or α^2 *Canum Venaticorum stars* after the prototype. The spectrum variations are accompanied by small variations (typically $0^m.05$) in brightness and color. The period, which is the rotation period of the star, is in the range $0^d.5$ to several days, or occasionally longer. An example is shown below in Figure 1.

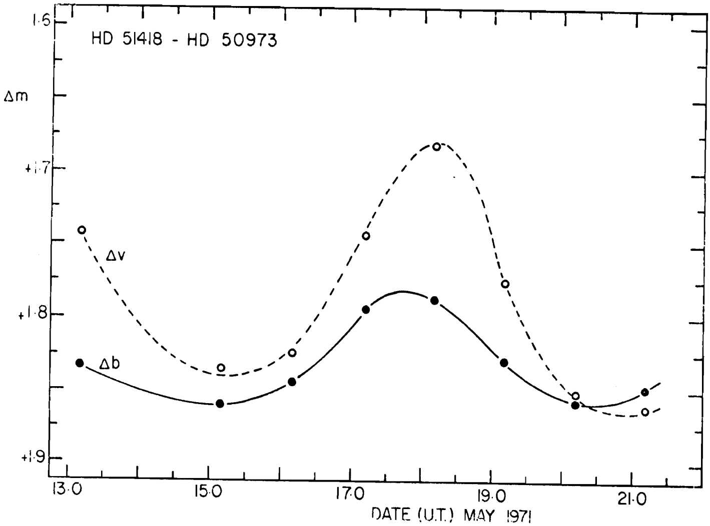


Fig. 1. The light curve of the peculiar A star HD 51418 in yellow light (v) and blue light (b). The observations were made differentially relative to HD 50973 (16 Lyn) using a 0.4m reflector at Kitt Peak National Observatory. The constancy of HD 50973 was established relative to HD 50037 (60 Aur). The period of HD 51418 is 5.4379 days, which is its rotation period. The range is $0^m.17$ in yellow light and $0^m.08$ in blue light, so the star is reddest when it is brightest. The range in yellow is larger than in any other known peculiar A star. Source: unpublished observations by the author. See also Gulliver and Winzer (1973)

The most crucial property of these stars was discovered by Horace W. Babcock around 1950: they have magnetic fields of up to 35,000 Gauss, not just in localized spots, but over their entire surface. Furthermore, the apparent strength of the magnetic field varies with the same period as the spectrum, brightness, and color. The behaviour of the stars can be explained by the *oblique rotator model* first proposed by D.W.N. Stibbs and developed by Armin J. Deutsch. According to this model, the stars have magnetic fields inclined at some angle to their rotation axis (hence oblique). The magnetic fields affect the brightness, color, and the concentrations of certain chemical elements, such that these are different at different magnetic latitudes. As the star rotates, all these properties appear to the observer to vary with a period which is the rotation period of the star.

Successful as the oblique rotator model is, there are several important questions still to be answered, the most fundamental being what is the origin of the strong magnetic field? The origin of the spectral peculiarities is a bit more certain. In the presence of a strong magnetic field, the atmosphere of the star is very stable. Chemical elements can then separate by diffusion. Some elements suffer more upward force due to radiation, and rise to the surface. Other elements suffer more downward force due to gravitation, and sink downward. For any given element, the balance between radiation and gravitation depends on the temperature of the atmosphere. Stars of different temperature will therefore have different spectral peculiarities; different elements will be over- or under-abundant.

The variations of brightness and color can also be explained. The brightness and color of the star's surface depend on the absorption properties of the atoms present. An over-abundance of the element europium in one region of the star's surface, for instance, may block radiation in the ultra-violet part of the spectrum and force the radiation out in the visual part of the spectrum. This makes that region of the star look redder and brighter in the visual. The actual shapes, amplitudes, and phases of the brightness and color curves are a complicated function of the age, rotation, temperature, and magnetic field geometry of the star.

C-2. THE RS CANUM VENATICORUM STARS

These spotted sunlike stars have recently become of great interest to photoelectric photometrists, especially those with small telescopes. These stars are discussed in detail in a separate chapter of this book. RS CVn stars are generally close binaries. Tidal interaction can speed up the rotation of the stars. Rapid rotation leads to stellar "activity" including large groups of starspots. These, along with the rotation of the star, provide the necessary prerequisites for rotational variability. RS Canum Venaticorum stars, and the two related groups mentioned below, have been extensively discussed at recent conferences (Dupree, 1980; Bonnet and Dupree, 1981; Giampapa and Golub, 1982).

C-3. THE BY DRACONIS STARS

The BY Draconis variables are dwarf K and M stars which show small amplitude (typically

$0^m.05$) brightness variability with a period of a few days. The cause is similar to that of the distortion wave (rotational variability) in the RS Canum Venaticorum stars, i.e. starspots on the photosphere of the star rotate in and out of the observer's field of view. There is additional evidence of stellar "activity" on these stars: Ca II and sometimes H emission lines in their spectra; and sometimes also flares in brightness. Some of them can therefore be classified as flare stars (UV Ceti stars) as well as BY Draconis stars.

The variability of these stars is difficult to detect and study, especially with small telescopes, because K and M dwarfs are intrinsically very faint. The brightest are far below naked-eye visibility, and the variability is very small. It can actually disappear and reappear (with a different phase) as starspots come and go. For this reason, BY Draconis stars are as much in need of regular monitoring as RS Canum Venaticorum stars are.

C-4. FK COMAE STARS

This name is applied to "active" cool giants which are apparently *single*. Their rapid rotation arises from some cause other than the direct tidal effect of a close companion. FK Com itself has strong chromospheric and coronal activity, rivalling that in the RS CVn stars. It has a spectral type of G2 III, V sin i $\sim$ 120 km/s, and a light curve with a period of $2^d.4$ and a variable range $\sim 0^m.1$. Bernard Bopp has raised the intriguing suggestion that FK Comae is a former close binary of the W UMa type, in which the two components have merged or are about to merge. The orbital angular momentum has thus been converted into the rotational angular momentum of a single star.

There are other single solar-type stars in which low-amplitude variability has been observed; the sun itself is an extreme example. Further examples of this phenomenon are gradually being discovered among the brighter F, G, and K type stars (Radick et al, 1982). In most of these cases, the rotation of the stars is probably intrinsic, rather that the result of some binary companion, past or present.

D. PULSATING VARIABLES

These variables can arbitrarily be divided according to their position in the Hertzsprung-Russell diagram: those in the Cepheid instability strip (Cepheids, δ Scuti stars, and ZZ Ceti stars), those in the red instability region, and those in or near the β Cephei instability strip. In addition, there are supergiant variables which are probably pulsating, but which contain elements of eruptive variability as well.

D-1. SMALL-AMPLITUDE CEPHEID VARIABLES

These can be sub-divided into two groups. In the first are short-period ($\leqq 8^d$), small-amplitude regular variables like Polaris, which are indistinguishable from ordinary short-period Cepheids except for their amplitude. A rather atypical example is shown below in Figure 2. The cause of the small amplitude is quite uncertain, though a recent study by Arellano Ferro (to be published) suggests that it may be related to their position on the red side of the instability strip. Polaris-like Cepheids are as numerous among the bright stars as ordinary Cepheids, but are harder to find, of course; some may yet be discovered.

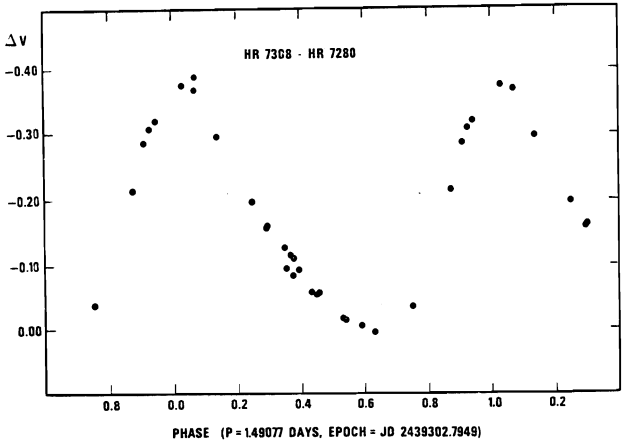


Fig. 2. The 1981 light curve of the small-amplitude Cepheid HR 7308 in yellow light (V). The observations were made differentially relative to HR 7280, using the 0.4 m reflector at the University of Toronto. The constancy of HR 7280 was established relative to HR 7253. The period of HR 7308 is 1.49 days, the shortest of any known Cepheid in our galaxy. The range in 1981 was nearly $0^{m}.4$ (which disqualifies it as microvariable), but the star is unusual in that the range varies between $0^{m}.4$ and $0^{m}.05$ in a period of 1210 days. The cause of this unique behaviour is not known. Source: Percy and Ford (1981).

In the second group are long-period ($\geq 40^{d}$), small-amplitude irregular variables of which the best example is probably 89 Her (Fernie, 1981). A list of such stars is given by Percy (1981). Because of their irregularity, moderate range and long period, they are appropriate targets for photoelectric photometrists with regular access to a small telescope. These stars appear to differ from ordinary Cepheids. In fact, there are virtually no ordinary Cepheids in our galaxy with periods longer than 40^d. The 89 Her-type stars pulsate irregularly at best, and their variability may be strongly influenced by the turbulence and low gravity of their atmospheres. They seem to form a bridge between the ordinary Cepheids and some of the supergiant variables discussed in section D-6.

D-2. DELTA SCUTI STARS

In the Hertzsprung-Russell diagram, these stars lie at the intersection of the Cepheid instability strip and the main sequence, which is where the majority of stars are found. Hence they are numerous: about 200 are known among the naked-eye stars. Virtually all of them have ranges $<0\overset{m}{.}1$; a range of $0\overset{m}{.}03$ would be considered typical. Those few with ranges $>0\overset{m}{.}3$ are sometimes called "dwarf Cepheids". This is because their radii are comparable to the sun's, whereas those of ordinary Cepheids are very much larger. Because of their small size, δ Scuti stars have short periods of pulsation: $0\overset{d}{.}03$ to $0\overset{d}{.}3$. The study of δ Scuti stars is particularly difficult, not only because of their small amplitudes and short periods, but also because their light curves are often irregular, in most cases because they are pulsating in two or more "modes" at the same time. A good example is shown in Figure 3. These stars lie in the downward extension of the Cepheid instability strip, which means that their spectral types are between A5 and F2. Within these limits, about 30% of all stars near the main sequence are δ Scuti stars with $\Delta m > 0\overset{m}{.}02$. It has been suggested that many of the other 70% are also δ Scuti stars, but with $\Delta m < 0\overset{m}{.}02$ and therefore difficult or impossible to detect.

There is a subset of the A5 - F2 stars which appears to be immune to δ Scuti pulsation. These are the Am stars, i.e. A stars with abnormally strong metallic lines in their spectra. These stars rotate slowly, and have very stable atmospheres. As a result, some metallic elements "float" to the surface by diffusion (as in the Ap stars), thus producing the abnormally strong lines in their spectra. Helium "sinks" downward from the atmosphere of the star, and is no longer able to contribute to the driving of the pulsation. This is enough to prevent the pulsation from occurring.

An excellent review of this and other aspects of δ Scuti stars has recently been published by Michel Breger (1979), the leading authority on the subject.

D-3. ZZ CETI STARS

These are white dwarf stars lying in the Cepheid instability strip. Their periods are a few hundred seconds and their ranges are typically $0\overset{m}{.}1$, but since the brightest of these variables is G226-29 with V = 12.24, they are clearly not of practical interest

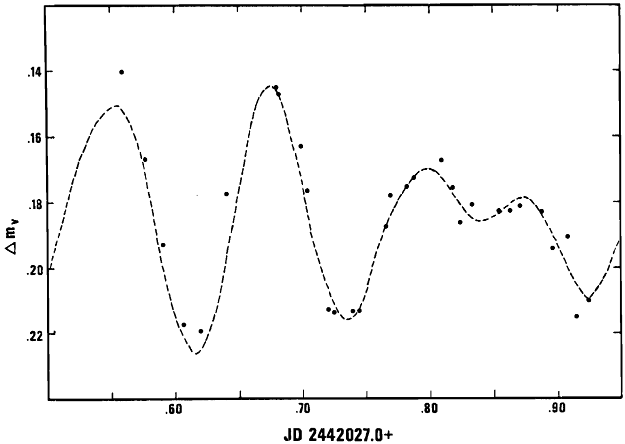


Fig. 3. The yellow (V) light curve of the δ Scuti star 44 Tau on December 10 - 11, 1973. The observations were made differentially relative to 42 Tau, using a 0.4 m reflector at Kitt Peak National Observatory. The constancy of 42 Tau has been checked by numerous observers since it is the standard comparison star for the peculiar A star 41 Tau. The light curve appears irregular, but it can be explained by assuming that the star is pulsating in two radial modes simultaneously: the fundamental (period of 0.145 day) and the first overtone (period of 0.112 day). The dashed line is a mathematical fit based upon this assumption. Source: Wizinowich and Percy (1979).

to most photoelectric photometrists, especially those with small telescopes!

D-4. BETA CEPHEI STARS

The β Cephei stars (sometimes called β Canis Majoris stars) are an interesting group of pulsating stars of early B type. According to present theory, they should not exist: stars hotter than Cepheids should all be stable! The cause of the pulsation in these stars is one of the major unsolved problems in the theory of variable stars.

These stars are of spectral type B0.5 - B2.5 III-IV, i.e. lying just above the upper main sequence. A large fraction of such stars are β Cephei stars, and since early

B stars are luminous and hence apparently bright, β Cephei stars are the most frequent variables among the 286 brightest stars in the Observer's Handbook. They include βCMa, βCru, αVir, βCen, αLup, and βCep, to mention only the α and β stars.

Their periods are about 2 to 7 hours, and their ranges in brightness and color are $\leq 0\overset{m}{.}2$; thus all of them are microvariables. Many show a slow increase and decrease in range called the *beat effect*, which is caused by the simultaneous presence of two or more pulsation modes with nearly equal periods. These usually include a radial (spherically symmetric) pulsation mode, as well as one or more non-radial modes.

Myron A. Smith has recently discovered another class of B type microvariables, called 53 Persei stars after the prototype, which undergo pure non-radial pulsation. In these stars, the most conspicuous variability is in the shape of the absorption lines in their spectra. There is also small variability in brightness, but hardly any in radial velocity or in temperature (hence, color). It is possible that some of the Be stars discussed in section E-1 are also undergoing non-radial pulsations (the next chapter in this book discusses this possibility in more detail).

Lesh and Aizenman (1978) have published an excellent review of the observed properties of the β Cephei stars.

D-5. LONG-PERIOD VARIABLES

Long-period variables are cool giant and supergiant stars. Microvariables of this type have been called SARV's: *small-amplitude red variables* (Eggen, 1973 a,b). Since it is the coolest giants and supergiants that are most prone to variability, have the largest ranges, and (because of their larger sizes) the longest periods, SARV's therefore tend to be less cool (M0 - M5 type) than full-blown long-period variables (M5 - M10 type) and tend to have shorter periods (10 - 100 days). It is likely that the sun will evolve into an SARV in a few billion years.

SARV's are numerous among the bright stars; and because they are bright, irregular, and poorly studied, they are in need of regular monitoring. They would thus appear to be an appropriate target for photoelectric photometrists with small telescopes. However, their red color causes several problems: it is hard to find non-variable comparison stars of similar color, and observations must be *rigorously* and *carefully* transformed to the UBV system.

The AAVSO has recently established a photoelectric photometry program containing many SARV's. This program is a natural outgrowth of the AAVSO's longstanding interest in red variables.

D-6. SUPERGIANT VARIABLES

The variability of yellow supergiants (spectral types F5 - G0 I: Cepheids) and red supergiants (spectral types M1 I and later: like Betelgeuse) is well known. What is less well known is that virtually all supergiants are variable, with ranges of a few hundredths of a magnitude, The more luminous the supergiant, the larger the range on the average. There is a slight increase in range among the B type stars, perhaps related to the β Cephei phenomenon. The range is particularly large among the yellow and red supergiants, and also among all of the cooler, most luminous stars. These conclusions were reached by André Maeder (1980) from a statistical study of 2420 photometric observations of 327 supergiants over 20 years.

Although supergiant variability is not strictly periodic, a characteristic time scale or "quasi-period" can be deduced from studies of individual stars (Burki, 1978). It ranges from about 10 days at B 2 Ia,to about 90 days at G0 Ia,to more than 300 days for such extreme supergiants as ρCas and HR8752. A typical bright example is shown in Figure 4. The time scale is related to the luminosity and the temperature of the star in a way which would suggest that the variability was due to pulsation. However, it is somewhat longer than the expected periods of radial pulsation. For this and other reasons, Meader (1980) suggested that the pulsation might be non-radial,driven by the deep convective motions which occur in the outer layers of the most luminous stars.

E. MISCELLANEOUS VARIABLES

This final section could include a wide variety of objects, including classes of microvariables not yet discovered. There are great numbers of variables, for instance, which are classified as *eruptive*: flare stars, novae and supernovae. Most of these have large ranges, but it is possible that small-scale flaring occurs on some stars (like our sun!); this would be seen as microvariability from a distance. Young nebular variables such as T Tauri stars show small-scale variability, but since T Tauri stars are intrinsically faint, they are not of practical interest to the photoelectric photometrist with a small telescope.

E-1. B EMISSION STARS

These stars *are* of practical interest, so much so that there is a separate chapter on them following this chapter. These are B stars which have shown emission in at least one hydrogen line on at least one occasion. Be stars are rapidly rotating stars, and the most widely accepted explanation for the Be phenomenon (at least in most Be stars) is that the emission arises in an expanding equatorial disc of gas driven off the star by rotational and radiative forces.

Be stars often show variability of emission and of brightness and color on a time

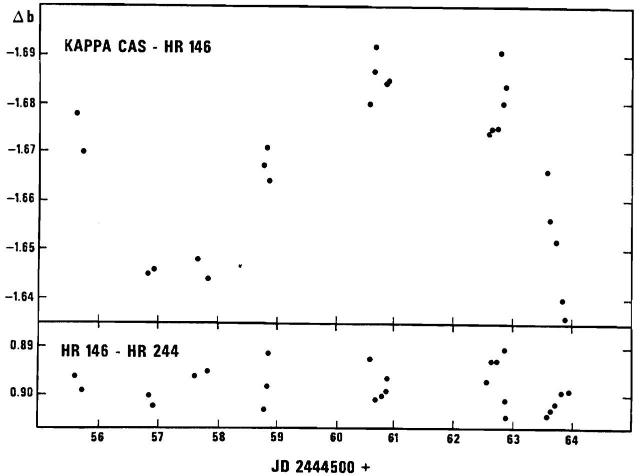


Fig. 4. The light curve of the B type supergiant variable κ Cas in blue light (b). The observations were made differentially relative to HR 146 using a 0.4 m reflector at Kitt Peak National Observatory. The constancy of HR 146 was established relative to HR 244 (lower panel). The variability of κ Cas and other supergiants is quite irregular, but there are characteristic time scales or "quasi-periods" which are correlated with the luminosity and temperature of the star. For κ Cas, the time scale is a few days. The range is typically $0^{m}.05$. Note that there is no significant hour-to-hour variability. Source: Percy and Welch (1983).

scale of weeks to decades, apparently because of changes (of unknown origin) in the amount of gas in the disc. There is also variability on time scales of days to weeks, often due to binarity. Finally, there is sometimes variability on time scales of hours to a day or more, due to non-radial pulsation or possibly to rotation.

In order to better understand the nature and cause of these forms of variability, astronomers at the Ondřejov Observatory in Czechoslovakia have recently organized an international campaign to obtain photoelectric photometry of the nearly 200 Be stars in the Yale Catalogue of Bright Stars. These stars are well suited to *careful* study by photoelectric photometrists with small telescopes.

REFERENCES

Bishop, R.L. (editor) 1982. "The Observer's Handbook for 1983" (Royal Astronomical Society of Canada ; Toronto)

Bonnet, R.M. and Dupree, A.K. (editors) 1981. "Solar Phenomena in Stars and Stellar Systems" (Reidel ; Dordrecht)

Breger, M. 1969. Astrophys. J. Suppl. 19, 79.

Breger, M. 1979. Publ. Astron. Soc. Pacific, 91, 5.

Burki, G. 1978. Astron. Astrophys., 65, 357.

Dupree, A.K. (editor) 1980. "Cool Stars, Stellar Systems, and the Sun", Smithsonian Astrophysical Observatory Special Report, #389.

Eggen, O.J. 1973a. Astrophys. J., 184, 793.

Eggen, O.J. 1973b. Mem. Roy. Astron. Soc., 77, 159.

Fernie, J.D. 1981. Astrophys. J., 243, 576.

Giampapa, M.S. and Golub, L. (editors) 1982. "Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun", Smithsonian Astrophysical Observatory Special Report, #392.

Gulliver, A.F. and Winzer, J.E. 1973. Astrophys. J. 183, 701.

Hoffleit, D. 1982. "Catalogue of Bright Stars" (Yale University Observatory ; New Haven)

Jerzykiewicz, M., Jarzebowski, T., Le Contel, J-M., and Musielok, B. 1978. Int. Astron. Union - Inf. Bull. Var. Stars #1508.

Lesh, J.R. and Aizenmann, M.L. 1978. Ann. Rev. Astron. Astrophys., 16, 215.

Maeder, A. 1980. Astron. Astrophys., 90, 311.

McCrosky, R.E. and Whitney, C.A. 1982. Int. Astron. Union - Inf. Bull. Var. Stars #2186.

North, P., Rufener, F., Figer, A. and Maurin, L. 1981. Int. Astron. Union - Inf. Bull. Var. Stars #2036.

Percy, J.R. 1981. J. Amer. Assoc. Var. Star Obs., 9, 64.

Percy, J.R. and Welch, D.L. 1983. Publ. Astron. Soc. Pacific, in press.

Percy, J.R. and Ford, R.P. 1981. J. Amer. Assoc. Var. Star Obs. 10, 53.

Radick, R.R., Hartmann, L., Mihalas, D., Worden, S.P., Africano, J.L., Klimke, A. and Tyson, E.T. 1982. Publ. Astron. Soc. Pacific, 94, 934.

Rufener, F. 1976. Astron. Astrophys. Suppl., 26, 275.

Rufener, F. and Bartholdi, P. 1982. Astron. Astrophys. Suppl., 48, 503.

Wizinowich, P. and Percy, J.R. 1979. Publ. Astron. Soc. Pacific, 91, 53.

5

PHOTOELECTRIC PHOTOMETRY OF Be STARS

PETR HARMANEC

Astronomical Institute
of the
Czechoslovak Academy of Sciences
251 65 Ondrejov
Czechoslovakia

Be stars are the stars of spectral type B (surface temperatures ranging from 10,000° to 30,000°K) which - at least in some epochs - exhibit hydrogen emission in their spectra. They apparently represent at least twenty percent of all B-type stars, and their basic physical characteristics do not seem to differ very much from their non-emission counterparts. Sometimes additional absorption lines, usually referred to as *shell lines*, are also visible in the spectrum.

The Be stars have been a fascination for observers ever since the spectrograph was introduced to astrophysics. From the many papers describing the spectra of Be stars, we know that they vary markedly on a time scale of years. Both emission and shell lines can disappear completely; if this happens, then what was once a Be star looks like a normal B-type star. Several years later emission and shell components can again be superposed on the normal B absorption spectrum. As a rule, this long-term variability is not strictly periodic, though it may be cyclic in some parameters. More recently, some shorter and less pronounced variations in the Be spectra have been recognized. In several cases, periodic variations of radial velocity and line profiles on a time scale ranging from days to hundreds of days were discovered. New detectors introduced to astrophysics during the last fifteen years enabled observers to shorten the exposure times of Be spectrograms. Thus, it has been possible to study rapid variations on a time scale of hours or even minutes. Such variations are generally rather small, and at least in some cases, their instrumental origin cannot be ruled out. Simultaneous observations of one star from two observatories would help to prove these variations real in particular cases.

In spite of considerable observational as well as theoretical efforts, the origin of emission and shell lines in the spectra of Be stars is not well understood. Most theoreticians agree that these lines must originate in extended envelopes enclosing these stars. Several mechanisms for the formation of such envelopes have been invoked. The first model proposed some fifty years ago stressed the role of rapid rotation in these objects. Later it became clear that the rotation itself is not able to produce such an envelope. Moreover, the rotational model can hardly explain the variations observed. An additional force is required to maintain the envelope. This could be some kind of stellar wind. Recently, a binary model for the Be phenomenon has been suggested. The formation of the envelope, the rapid rotation, and some types of observed variations are believed to be consequences of mass transfer from an invisible companion onto the Be star. Secondary components actually have been detected in some Be stars, and orbital modulation has been found in several spectroscopic and photometric data. In other cases, however, no signs of duplicity have been discovered so far. Finally, there have been some attempts to explain variations of Be stars as a result of some sort of atmospheric pulsations.

Contrary to the rich spectroscopic evidence of the variability of Be stars, little was known about their *light* variability. Until recently, systematic photoelectric observations of Be stars were rather rare, It is true that there were some exceptions. For example, Guthnick (Guthnick 1918, 1941, and Groeneveld 1944) observed o And photoelectrically as early as during World War I, and later suggested a period of 1.577 days for its light variations. However most of the photoelectric observations of Be stars were only statistical studies of a large group of objects. Such studies, though very useful, were usually not intended to investigate variability of Be stars, but just to study the properties of Be stars as one specific group of galactic objects. Papers by Stebbins *et al* (1940), Hiltner (1956), Mendoza (1958), Crawford (1963), Cousins and Stoy (1963), or Guetter (1974) may serve as examples of such observations.

Probably the first systematic search for the light variations of Be stars was undertaken by Feinstein (1968, 1970, 1975) who observed a number of southern Be stars in the UBV system repeatedly for several years. Unfortunately, Feinstein observed Be stars directly (as did most of his predecessors) rather than using comparison stars. Thus only the variations larger than $\simeq 0\overset{m}{.}1$ can be considered to be safely detected. A similar observational program (but using the 13-color photometry) has recently been started by Alvarez (1981) and Alvarez and Schuster (1981, 1982).

Sharov and Lyuty (1972 a,b, 1973, 1975, 1976, 1977, 1980) have undertaken one of the first long-lasting systematic photoelectric studies of the light variations of one particular Be star, BU Tau, using *differential* UBV photomety. They discovered that the remarkable long-term variations of this star correlated with the re-appearance of the emission-line and shell spectrum. Other pioneering investigations of Be stars as variables (measured differentially relative to comparison stars) were those by Lynds (1959a,b and 1960), Haupt, and Schroll (1974), Hill (1967 a,b), and Hill *et al* (1976).

Sometimes, the discovery of light variability was rather amusing. For example, the spectacular light variations of V 1294 Aql (HD 184279) are well documented mainly because the star was selected as a secondary standard of the UBV system.

It is virtually impossible to enumerate all important photoelectric studies of Be stars in this chapter, however I have attempted to collect the most important studies in the references to follow the chapter. (Possible omissions are exclusively due to the ignorance of the author, who apologizes for them in advance.)

For a long time, Be stars have been known to exhibit pronounced spectral variations on a time scale of years (McLaughlin 1961). It *was* known from photographic and visual observations that several Be stars (e.g. γ Cas or P Cyg) underwent rather spectacular, apparently non-periodic, long-term light variations on a time scale of years, but these cases were considered to be exceptions rather than characteristic examples of the Be-star behavior. In contrast, little was known about their photometric behavior. Only the studies by Feinstein (1968, 1970, 1975), Nordh and Olofsson (1974 a,b, 1977), Sharov and Lyuty (1976, 1980), Ferrer and Jaschek (1971), Harmanec *et al* (1978, 1979, 1980 a), Horn *et al* (1982 a,b), Koubský *et al* (1980 a), and Dachs (1982) led to the realization that the long-term light variations of Be stars also represent the most pronounced light variations observed for them.

A group of Czechoslovak and Yugoslav astronomers started a systematic search for light variations of a number of bright northern Be stars, using differential UBV photometry at the newly founded (1972) Hvar Observatory, Yugoslavia. They suggested that an international observing campaign be organized during which a large group of bright Be stars would be observed for several years (Harmanec, *et al* 1980 a). The idea has been accepted and supported by the Working Group on Be stars of the IAU Commision 29 in 1980. Harmanec, Horn, and Koubský of Ondrejov Observatory were asked to organize and co-ordinate the entire campaign.

As a first step, about 150 Be stars brighter than $6^{m}.5$ and north of -20° declination were selected. Suitable comparison and check stars having Johnson's UBV measurements (Johnson, *et al* 1966) available were chosen, and in collaboration with Dr. N. Kukarkina of Moscow, carefully checked not to be known or suspected variables. (Soon, some of them had to be, and probably will still have to be replaced because of their variability discovered during the campaign observations.) The use of *obligatory* comparison and check stars and a careful transformation of the data into a well-defined photometric system both represent the *conditio sine qua non* to ensure compatibility of the data obtained by different observers. The campaign has been organized via Be-star Newsletters in which the detailed instructions (in No. 2) as well as progress reports are regularly published (c.f. Harmanec, *et al* 1981c). In addition, the campaign was discussed at two international meetings (Harmanec, *et al* 1981e, 1982b). A computerized listing of the observing program including the objects, comparison stars, etc. is available on request from the organizers.

The purpose of the whole campaign is: (1) to establish for a statistically significant group of Be stars, how many of them are variable on time scales shorter than, say, ten years, (2) to recognize which types of photometric variability do occur in Be stars and how they correlate with other variations observed.

With regard to point 2, it is very important that Barker (1981 a,b, 1982 a,b,c) has organized a simultaneous campaign for spectroscopic observations of the same group of Be stars.

There are other important observing campaigns. Since 1980, a group of American and

West-European astronomers has observed five of the stars included in the photometric campaign (ξ Oph, γ Cas, 59 Cyg, θ CrB, and HR 2142) simultaneously in the optical, X-ray, UV, and IR spectral bands, using all available observational techniques. Some European Southern Observatory observers are preparing a campaign for observing long-term photometric variations of various stars, including selected Be stars. In 1976, Percy and his collaborators started a systematic search for *short-term* (0.1 to 2 days) light variability of early B stars including Be stars.

Let us try to summarize now what is known about the light variability of Be stars on the basis of the observational data accumulated so far.

1. Presence of the variations. Although some Be stars observed turned out to be constant within the $0^m.01$ limit over several years, most of them do exhibit some variations on various time scales shorter than ten years. Usually these variations are not very pronounced ones. Their amplitude only rarely exceeds $0^m.5$.

2. Long-term variability (years). Available data is still insufficient to allow any firm conclusions, however at least three distinct types of the long-term variability have been definitely recognized. The variability of type 1 (c.f. Sharov and Lyuty 1976, Harmanec, *et al* 1978, Hirata 1978, Horn, *et al* 1982b) is illustrated in Figure 1. It was found for three Be stars (BU Tau, 88 Her, V 1294 Aql) that the phase of maximum light corresponded to a phase when the hydrogen emission and metallic shell lines disappeared from their spectra. A relatively rapid light decrease with a tendency to two subsequent minima always accompanied the re-appearance of the H I emission lines and the metallic shell spectrum. Note that the duration of the light decrease is remarkably similar for all three objects regardless of their different spectral subtypes. Doazan, *et al* (1982) pointed out that the light curves of this type are in some sense *negatives* of the light curves of novae, although with a smaller amplitude. According to Percy (priv.com.), they also resemble the light curves of R CrB stars.

As to the color variations accompanying these light changes, it is notable that the brightening is always accompanied by *blueing* of both the B-V and U-B indices, and vice versa. This behavior differs from the "most typical" behavior of Be stars found by Nordh and Olofsson (1977) and confirmed by Hirata (1982) and Hirata and Hubert-Delplace (1981). These authors investigated statistically the long-term light and color variations of a number of Be stars compiled from various sources and invariably concluded that the brightening of the V magnitude is in most cases accompanied by *reddening* of the B-V, and *blueing* of the U-B indices. It seems to indicate another, type 2 variability. The difference between the two types of variations is the most notable in the U-B vs B-V diagram. During type 1 variations the objects move along the main sequence in this diagram, changing their photometric spectral type but not the luminosity class. For type 2 variations the objects change their photometric luminosity class from dwarfs to bright supergiants and back, while maintaining their photometric spectral subclasses. Prototypes of type 2 variations are πAqr (Nordh and Olofsson 1977) and EW Lac (Harmanec *et al* 1979). Dachs (1982) showed that for type 2 variations, brightening of the V magnitude is accompanied also by the brightening in the near infrared bands

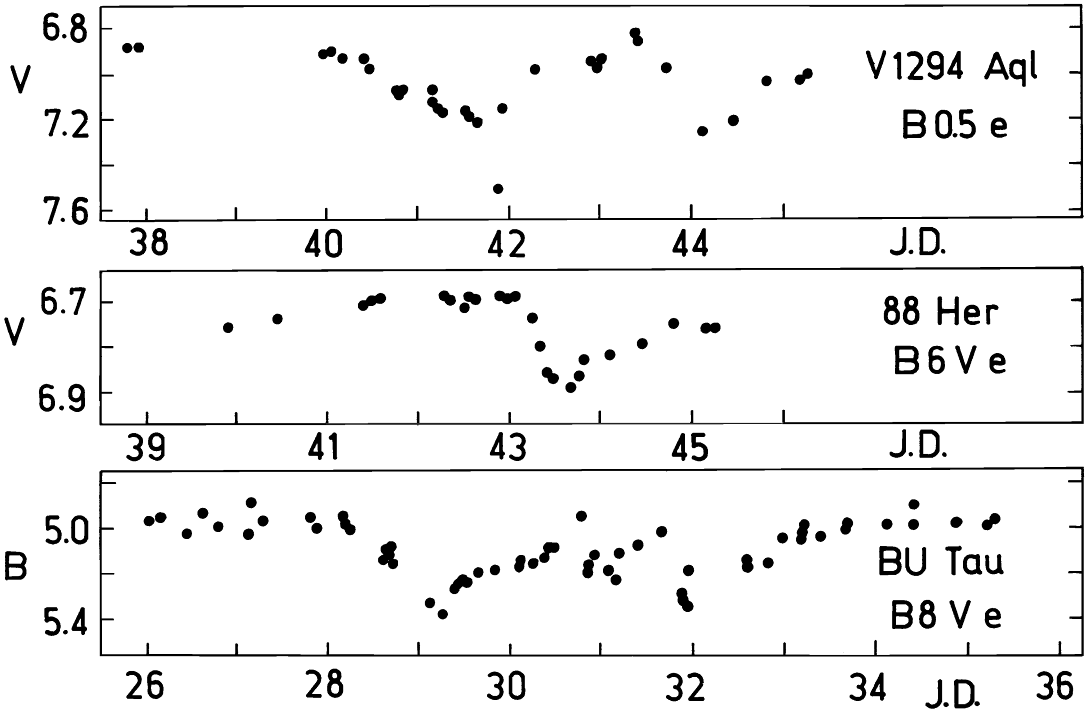


Fig. 1. Long-term light variations of type 1 for three Be stars (adapted from Horn *et al* 1982b). Note that the time scale is in thousands of days with 2400000 subtracted.

He also found that in the variations of <u>type 3</u>, which he calls the H_α emission saturation, the intensity of the emission from the envelope remains constant while large light variations occur in visual and infrared magnitudes (the ratio $\Delta L/\Delta V$ being of the order of unity). A representative of the type 3 variability is χ Oph.

Nordh and Olofsson (1974b, 1977) and Harmanec, *et al* (1978) suggested that the long-term light variations of Be stars can be qualitatively understood on assumption that the circumstellar envelopes are variable in time. Stepiński (1980) put these considerations on a more quantitative ground, however, why the envelope structure should vary in time remains to be explained.

3. <u>Intermediate variations (weeks to months)</u>. These variations are also not sufficiently well investigated. It seems however that many known cases of this type of variation are somehow connected with the binarity of the Be stars in question. In some cases, normal geometrical eclipses of binary components are observed (β Lyr, RX Cas, SX Cas, TT Hya, etc.). For some other objects, an eclipse of the Be component by a gas stream flowing from the secondary is responsible for the variations, especially in the U band (e.g. AX Mon or KX And). In still other cases the interpretation of the periodic light variations following the binary orbital period is not clear (see Fig.2). A general characteristic of most of these variations is that though they are apparently connected with the binary motion, the light curves do not repeat exactly from cycle to cycle. Kalv (1979) found that the *shape* of the light curve of RX Cas (orbital period of 32 days) varies with a period of 517 days. Whether such a regularity can be found also in other cases remains to be investigated. Sometimes the deviations from the *average* light curve are so strong that the periodicity of the variations is not apparent until many cycles are covered by the observations. It is difficult, therefore, to conclude whether or not some limited observations of particular Be stars showing apparently non-periodic light variations on a time scale of weeks to months are of the above-mentioned origin. Clearly, the continuing observing campaign will be extremely valuable to clarify this particular problem.

4. <u>Rapid variations (hours to days)</u>. Although the rapid variations of Be stars usually have rather small amplitudes (less than $0\overset{m}{.}1$ in most cases) and are not therefore easily detectable, they seem to be potentially very important for understanding the nature of Be stars. At the same time, they are probably also the most puzzling of the light variations observed. Before trying to classify these variations, let us consider several particular examples:

a) <u>o And (HD 217675)</u>. As mentioned before, this is one of the first Be stars observed photoelectrically. Guthnick (1941) and Groeneveld (1944) found light variations with a period of 1.577 days and two minima and maxima each cycle. For years, the star was believed to be a contact eclipsing binary. Schmidt (1959) published new photoelectric observations and derived a period of 1.5998 days. Archer (1958, 1959) apparently folded his own observations on the assumption of a single wave each period and arrived at a value of 0.788 days - about one half of Gutnick's period. He suggested that the object is a pulsating star, similar to RR Lyr stars. He also pointed out that the light variations were *absent* or very small in some epochs and that their presence may be connected

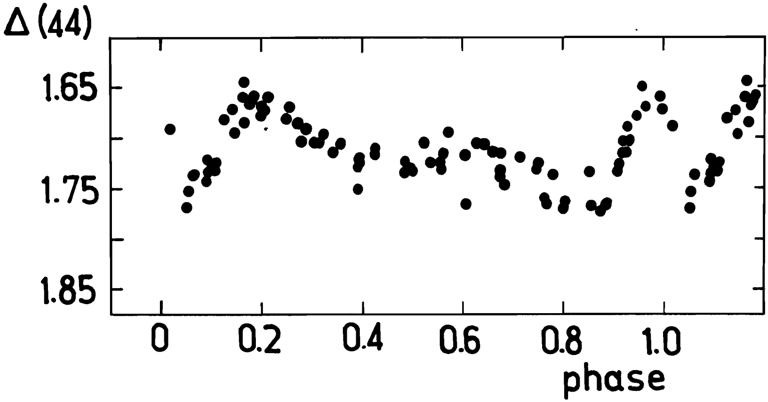


Fig. 2. The light curve of V1507 Cyg = HD 187399 as observed by Hill *et al* (1976) in 1972 - 1973. The measurements were obtained in the DAO photometric system. Phases are computed according to the ephemeris JD 2432465.98 + 27.97 x E.

with the formation of a new shell surrounding the star. Olsen (1972) obtained new observations of o And and concluded that if the variations are periodic, the most probable value of the period is 1.018 days. Bossi, *et al* (1977) observed the star after the re-appearance of the shell spectrum in 1975 and suspected a period of 0.84 days. Later on, Guerrero and Mantegazza (1979) suggested that the light variations of o And have no real periodicity and are of a stochastic origin. Padalia (1978) announced that according to his UBV observations the star was almost invariable during the period of October 1976 - December 1977. In particular, he failed to find any support for Schmidt's (1959) or Olsen's (1972) period. I and my colleagues of Ondrejov Observatory have spent much time analyzing all available sets of photometric measurements of the star, including unpublished Hvar data (c.f. Horn, *et al* 1982a). It turned out that:
(i). no period satisfying all sets of observations could be found, and (ii). the analyses of the data by original authors were painfully incomplete.
For example, at least ten almost equally good "periods" can be found in Schmidt's data, which are spaced rather unconveniently in time. Olsen (1972) states that he searched for periods between 0.4 and 4.8 days and gives 1.018 days as the best period. Yet, I found that a sine curve with a period of about 0.938 days fits his data better.

Many other authors simply quoted and accepted some of the periods proposed. It created an impression that the characteristic periods of repeatibility of the light variations of o And cluster around some specific values (c.f. Baade 1981) but I am afraid this only remains to be proven.

In conclusion, the problem of the light variations of o And remains a puzzle. The only thing which can be suspected is that the presence of rapid variations is somehow connected with the presence of the shell spectrum. Horn, *et al* (1982a) clearly showed that, in addition to occasional rapid variations, o And also exhibits long-term light changes of a much larger amplitude.

b) <u>EW Lac (HD 217050)</u>. Walker (1953) observed this star photoelectrically in 1951 and 1952 and found a rapid variability which could be reconciled with a period of 0.7364 days in 1951, but 0.800 days in 1952. Moreover, the variations were absent on some nights, so he had to assume a highly variable amplitude of the changes. The problem is that Walker used 14 Lac as his comparison star, but 14 Lac is a Be star which is now also known to vary on a time scale of days. Later data by Walker show the variations without any apparent periodicity. Walker (1958) interpreted rapid variations as caused by rotating starspots. Lester (1975) observed the star again in the summer of 1972 using Strömgen ubvy filters, and found variations with a characteristic time scale of 0.7 days, with wavelength behavior suggestive of temperature changes in an early-type atmosphere. Once again, no true periodicity of rapid variations could be found, but very pronounced long-term variations of a larger amplitude were found (Harmanec, *et al* 1979).

c) <u>28 CMa (HD 56139)</u>. Baade (1982a) discovered the presence of periodic radial-velocity and line-profile variations of this Be star with a stable period of 1.37 days. In an effort to understand the nature of these variations, he attempted to observe simultaneous light variations. However, his search was unsuccessful because of a slight variability of the comparison star used. Still, he was able to conclude that light variations larger than

$0\overset{m}{.}03$ on a short time scale were not present. Recently, Baade (1982b) found very small, rapid variations of 28 CMa (full amplitude $0\overset{m}{.}007$) with a period of 0.4353 days! Baade proposed that the radial-velocity and light variations may correspond to various modes of a non-radial pulsation of the star combined with a rapid rotation against the sense of the travelling wave. Feinstein (1970 and priv.com.) and Baade (1982b) found also long-term light and spectral variations of 28 CMa but their character is unclear because of lack of data.

d) EM Cep (HD208392). Light variability of this star was discovered by Lynds (1959a). Lynds was aware of two possible interpretations of his observations: the data could be reconciled either with a roughly sinusoidal curve with a 0.4-day period or with a light curve having two similar minima and maxima each cycle and a period of 0.8 days. He preferred the latter case and suggested that EM Cep is a very close eclipsing binary. His idea has been accepted by many other investigators in spite of Rachkovskaya's (1975) finding which was later confirmed (Hilditch, *et al* 1982) that no pronounced radial-velocity variations accompany the light changes. Rachkovskaya suggested that the light variations are induced by a pulsation or by rotation of the star, rather than by binarity of the object. There was some controversy in the astronomical literature as to whether the period of EM Cep varies or not. Breinhorst and Karimie (1980) showed that the period of 0.806 days has remained constant over the whole period covered by available data and that the impression of its variability was caused by interchanging primary and secondary minima by some authors. This happened due to the fact that the shape of the light curve and relative depths of the two minima vary with time. It is remarkable that besides these changes of the shape of the light curve, EM Cep *does not exhibit* any long-term light variations, though it *does exhibit* pronounced long-term variations in its spectrum.

e) LQ And (HD 224559). The light variability of this star was discovered by Percy and Lane (1977) and later confirmed by further observations by Percy and his collaborators. Percy (1982) showed that a period of 0.31 days can be found in all available data sets and suggested that the star is a non-radial pulsator. Harmanec (1983) analyzed Percy's observations and concluded that a 0.62-day variation with two similar minima and maxima (following each other after 0.45^{P}, and 0.55^{P}, respectively) provides a better fit of the data. He suggested that the light variations of LQ And, EM Cep, and a helium-rich Be star σ Ori E, may all be caused by the rotation of these objects combined with the non-uniform brightness distribution on their surfaces.

f) λ Eri (HD 33328). This Be star exhibits periodic variability with a stable period of 0.701538 days, both in photometric and radial-velocity data secured over several years. However the amplitude of these variations varies from zero up to $0\overset{m}{.}1$ in some epochs (Bolton 1982, Percy 1981a).

These few examples clearly show that no universal pattern of rapid variations of Be stars is apparent. In fact, the effort to establish true periods of these variations has been unsuccessful in most cases. It may indicate either that inappropriate methods for finding periods were used or that some of these variations are not periodic but stochastic in origin - as suggested, for example, by Guerrero and Mantegazza (1979). On the other hand, the cases for which stable periods were found are very interesting and probably important for understanding the structure of Be stars. From the previous discussion of individual stars it follows that rapidly variable Be stars may be the relatives of either the pulsating β Cep stars or the rotating Ap stars depending on the nature of their variations. If the latter would turn out to be true, it could provide a means to study dependence of rotational periods of Be stars on other physical parameters.

5. Relation between the variations on various timescales. Simultaneous presence of rapid and slower photometric variations was found for a number of Be stars (e.g. o And, EW Lac, CX Dra, AX Mon, V 923 Aql, etc.). Yet, it seems that for some rapid variables, no pronounced long-term changes occur (e.g. EM Cep and LQ And), while for some slowly varying Be stars the rapid variations are definitely absent (88 Her). At present, it is not even clear if the division of the variations into slow and rapid is an artificial one. For example, in Baade's (1982a) concept of non-radial pulsations coupled with rapid rotation, it is possible to reproduce any period from the range of β Cep stars (~0.15 days) to several years. For known binaries it would be interesting to see what is the relation between the rapid variations and the orbital modulation, etc.

6. Summary.

1. In order to understand the nature of the variations of Be stars, it will be necessary to observe many of them patiently for many years, using various observational techniques including photoelectric photometry.
2. Continued observing campaigns can be especially important for disclosing the nature of long-term variations, and for providing continuous monitoring of interesting cases of rapid variations by several observers in different geographic longitudes.
3. Even the photometric observers not participating in campaign observations should transform their data into some well-defined photometric system to save information about the long-term variability.

ACKNOWLEGEMENTS

The author is deeply obliged to Dr. J.R. Percy for the critical reading of the manuscript and for valuable comments which helped to improve the presentation and style of the text. Discussions about the subject with Dr. P. Koubský are also acknowledged.

REFERENCES

The following abbreviations are used for the proceedings of three recent conferences in the references below:

Be 70 - Be and shell stars, IAU Symp. No. 70, edited by A. Slettebak, Reidel
Be 98 - Be stars, IAU Symp. No. 98, edited by M. Jaschek and H.G. Groth, Reidel
WPB - Workshop on pulsating B stars, edited by G.E.V.O.N. and C. Sterken, Nice Obs. Publ.

1. Alvarez M. (1981) WPB, 247.
2. Alvarez M., Schuster W.J. (1981) Rev. Mex. Astron. Astrophys. 6, 163.
3. Alvarez M., Schuster W.J. (1982) Rev. Mex. Astron. Astrophys. 5, 173.
4. Archer S. (1958) Observatory 78, 250.
5. Archer S. (1959) Observatory 79, 99.
6. Baade D. (1981) WPB, 267.
7. Baade D. (1982a) Astron. Astrophys. 105, 65.
8. Baade D. (1982b) Astron. Astrophys. 110, L15.
9. Badalia J.K.,Gurm H.S. (1982) Inf. Bull. Var. Stars 2163.
10. Bakos, G.A., Tremko J. (1975) J. Roy. Astron. Soc. Canada 69, 307.
11. Barker P.K. (1981a) Be Newsletter 3, 14.
12. Barker P.K. (1981b) Be Newsletter 4, 22.
13. Barker P.K. (1982a) Be 98, 275.
14. Barker P.K. (1982b) Be Newsletter 5, 8.
15. Barker P.K. (1982c) Be Newsletter 6, 34.
16. Boulton C.T. (1982) Be 98, 181.
17. Bossi M., Guerrero G., Mantegazza L. (1976) Inf. Bull. Var. Stars #1095.
18. Bossi M., Guerrero G., Mantegazza L. (1977) Astron. Astrophys Suppl. 29, 327.
19. Bossi M., Guerrero G., Mantegazza L., Scardia M. (1980) Astrophys. Spa. Sci. 72, 433.
20. Bossi M., Gureereo G., Mantegazza L., Scardia M. (1982) Inf. Bull. Var. Stars #2082.
21. Bouigue R. (1959) Toulouse Ann. 27, 47.
22. Bozić H., Muminović M., Pavlovski K., Stupar M., Harmanec P., Horn J., Koubský P. (1980) Inf. Bull. Var. Stars #2123.
23. Breinhorst R.A., Karimie M.T. (1980) Publ. Astron. Soc. Pacific 92, 432.
24. Cousins A.W.J. (1964) Mon. Not. Roy. Astron. Soc. South Afroca 23, 175.
25. Cousins A.W.J. (1965) Mon. Not. Roy. Astron. Soc. South Africa 24, 120.
26. Cousins A.W.J., Stoy R.H. (1963) Roy. Obs. Bull. #64.
27. Cowley A.P. (1964) Astrophys. J. 139, 817.
28. Crawford D.L. (1963) Astrophys. J. 137, 530.
29. Crostesci C., Oprescu G., Suran M.D. (1981) Inf. Bull. Var. Stars #2050.
30. Dachs J. (1982) Be 98, 19.
31. Dahn C.C., Guetter H.H. (1973) Astrophys. J. 179, 551.
32. Dapergolas A., Di Cola G., Guarnieri A., Madama G. (1981) Inf. Bull. Var. Stars #1920
33. Detre L. (1969) in "Non-Periodic Phenomena in Variable Stars", Academic Press, Budapest, p. 188.
34. Doazan V., Harmanec P., Koubský P., Krpata J., Žďárský F. (1982) Astron. Astrophys. 115, 138.
35. Dworak T.Z. (1976) Inf. Bull. Var. Stars #1081.
36. Eggen O.J. (1968) Roy. Obs. Bull. # 137.
37. Elst E.W. (1979) Inf. Bull. Var. Stars #1697.
38. Feinstein A. (1968) Z. Astrophys. 68, 29.
39. Feinstein A. (1970) Publ. Astron. Soc. Pacific 82, 132.
40. Feinstein A. (1975) Publ. Astron. Soc. Pacific 87, 603.
41. Feinstein A., Marraco H.G. (1979) Astron. J. 84, 1713.
42. Feinstein A., Marraco H.G. (1981) Publ. Astron. Soc. Pacific 93, 110.
43. Fernie J.D. (1975) Astrophys. J. 201, 179.
44. Ferrer L., Jaschek C. (1971) Publ. Astron. Soc. Pacific 83, 346.
45. Golay M. (1979) Publ. Obs. Astron. Strasbourg 6, 89.

46. Golay M., Cramer N., Nicolet B. (1979) Publ. Obs. Astron. Strasbourg 6, 101.
47. Golay M., Mauron N. (1982) Astron. Astrophys. Suppl. 47, 547.
48. Groeneveld I. (1944) Veröff. Sternwarte Heidelberg (Königstuhl) 14, 43.
49. Guerrero G., Mantegazza L. (1979) Astron. Astrophys. Suppl. 36, 471.
50. Guetter H.H. (1974) Publ. Astron. Soc. Pacific 86, 795.
51. Guthnick P. (1918) Veröff. Berlin Babelsberg 2, 113.
52. Guthnick P. (1941) Vierteljahrsschrift Astron. Gesell. 76, 62.
53. Guthnick P., Prager R. (1930) Astron. Nachr. 239, 14.
54. Haefner R., Metz K., Schoembs R. (1975) Astron. Astrophys. 38, 203.
55. Häggkvist L., Oja T. (1966) Arkiv Astron. 4, 137.
56. Harmanec P. (1983) Bull. Astron. Inst. Czech. #34.
57. Harmanec P., Horn J., Koubský P., Kríz S., Ivanović Z., Pavlovski K. (1977) Inf. Bull. Var. Stars # 1324.
58. Harmanec P., Horn J., Koubský P., Kríz S., Zdárský F., Papousek J., Doazan V., Bourdonneau B., Baldinelli L., Ghedini S., Pavlovski K. (1978) Bull. Astron. Inst. Czech. 29, 278.
59. Harmanec P., Horn J., Koubský P., Zdárský F., Kríz S., Pavlovski K. (1979) Inf. Bull. Var. Stars #1555.
60. Harmanec P., Horn J., Koubský P., Zdárský F., Kríz S., Pavlovski K. (1980a) Bull. Astron. Inst. Czech. 31, 144.
61. Harmanec P., Horn J.,Koubský P. (1980b) Be Newsletter 2, 3.
62. Harmanec P., Horn J., Koubský P. (1981a) Be Newsletter 3, 12.
63. Harmanec P., Horn J., Koubský P. (1981b) Be Newsletter 4, 12.
64. Harmanec P., Horn J., Koubský P. (1981c) I.A.P.P.P. Comm. 4, 11.
65. Harmanec P., Horn J., Koubský P., Ziznovský J. (1981d) Inf. Bull. Var. Stars #1931.
66. Harmanec P., Horn J., Koubský P. (1981e) WPB, 397.
67. Harmanec P., Horn J., Koubský P. (1982a) Be Newsletter 5, 6.
68. Harmanec P., Horn J., Koubský P. (1982b) Be 98, 269.
69. Harmanec P., Horn J., Koubský P. (1983) Be Newsletter 7.
70. Haupt H.F., Schroll A. (1974) Astron. Astrophys. Suppl. 15, 311.
71. Heck A., Manfroid J. (1980) Astron. Astrophys. Suppl. 42, 311.
72. Hilditch R.W., McLean B.J., Reid I.N. (1982) Mon. Not. Roy. Astron. Soc. 200, 1153.
73. Hill G. (1967a) Astrophys. J. Suppl. 14, 263.
74. Hill G. (1967b) Astrophys. J. Suppl. 14, 301.
75. Hill G., Hilditch R.W., Pfannenschmidt E.L. (1976) Pub. Dominion Astrophys. Obs. 15, 1.
76. Hiltner W.A. (1956) Astrophys, J. Suppl. 2, 389.
77. Hirata R. (1978) Inf. Bull. Var. Stars No. 1496.
78. Hirata R. (1982) Be 98, 41.
79. Hirata R., Hubert-Delplace A.M. (1981) WPB, 217.
80. Hopp. U., Witzigmann S. (1979) Inf. Bull. Var. Stars No. 1782.
81. Hopp. U., Witzigmann S., Geyer E.H. (1982) I.B.V.S. No. 2148.
82. Horn J., Koubský P., Arsenijević J., Grygar J., Harmanec P., Krpata J., Kríz S., Pavlovski K. (1982a) Be 98, 315.
83. Horn J., Bozić H., Harmanec P., Koubský P., Pavlovski K., Zdárský F. (1982b) Bull. Astron. Inst. Czech. 33, 308.
84. Jackisch G. (1963) Veröff. Sternwarte Sonneberg 5, 227.

85. Jaschek C., Conde H., deSierra A.C. (1964) Publ. Obs. Astron. La Plata, Ser. Astron. 28, 2.
86. Johnson H.L., Mitchell R.I., Iriarte B., Wisniewski W.Z. (1966) Com. Lun. Planet. Lab. 4, 99.
87. Johnson K. (1970) Publ. Astron. Soc. Pacific 82, 1093.
88. Kalv P. (1979) Publ. Tartu Astrophys. Obs. #58, 3.
89. Karimie M.T. (1979) Inf. Bull. Var. Stars #1594.
90. Koubský P. Harmanec P., Horn J., Jerzykiewicz M., Kříž S., Papousek J., Pavlovski K., Ždárský F. (1980a) Bull. Astron. Inst. Czech. 31, 75.
91. Koubský P., Harmanec P., Horn J., Jerzykiewicz M., Kříž S., Pavlovski K., Ždárský F. (1980b) Acta Univ. Carolinae, Mat. and Phys. 21, 33.
92. Kreiner J.M., Tremko J. (1979) Acta Astron. 29, 97.
93. Kříž S., Arsenijević J., Grygar J., Harmanec P., Horn J., Koubský P., Pavlovski K., Zverko J., Ždárský F. (1980) Bull. Astron. Inst. Czech. 31, 284.
94. Lake R. (1965) Mon. Not. Roy. Astron. Soc. South Africa 24, 41.
95. Landis H.J., Lovell H.P., Hall D.S., Uckotter D.G. (1977) Acta Astron. 27, 265.
96. Lester D.F. (1975) Publ. Astron. Soc. Pacific 87, 177.
97. Lynds C.R. (1959a) Astrophys. J. 130, 577.
98. Lynds C.R. (1959b) Astrophys. J. 130, 603.
99. Lynds C.R. (1960) Astrophys. J. 131, 390.
100. Magalashvili N.L., Kumsishvili J.I. (1969) Abastumani Bull. 37, 1.
101. Magalashvili N.L., Kumsishvili J.I. (1980) Inf. Bull. Var. Stars #1868.
102. McLaughlin D.B. (1961) J. Roy. Astron. Soc. Canada 55, 13 and 73.
103. Mendoza E.E. (1958) Astrophys. J. 128, 207.
104. Merlin P. (1975) Astron. Astrophys. 39, 139.
105. Merrill P.W., Burwell C.G. (1933) Astrophys. J. 78, 87.
106. Merrill P.W., Burwell C.G. (1943) Astrophys. J. 98, 153.
107. Merrill P.W., Burwell C.G. (1949) Astrophys. J. 110, 387.
108. Nakagiri M., Hirata R. (1979) Inf. Bull. Var. Stars #1565.
109. Nekrasova S.V., Nikonov V.B., Rybka E. (1965) Izv. Krym 34, 69.
110. Nikonov V.B., Kharadze E., Kulikovski P. (1936) Observatory 59, 88.
111. Nikonov V.B., Kharadze E., Kulikovski P. (1937) Abastumani Bull. 1, 38.
112. Nikonov V.B., Kharadze E., Kulikovski P. (1938) Abastumani Bull. 2, 23.
113. Nordh H.L., Olofsson S.G. (1974a) Astron. Astrophys. 31, 343.
114. Nordh H.L., Olofsson S.G. (1974b) Stockholm Obs. Report #7.
115. Nordh H.L., Olofsson S.G. (1977) Astron. Astrophys. 56, 117.
116. Olsen E.H. (1972) Astron. Astrophys. 20, 167.
117. Padalia T.D. (1978) Inf. Bull. Var. Stars #1477.
118. Page A.A. (1981) Catalogue, Spectrum and Magnitude Data Bank of Be Stars, Mt. Tamborine Obs. Publ. #2.
119. Page A.A., Page B. (1970) Proc. Astron. Soc. Australia 7, 324.
120. Pavlovski K., Harmanec P., Horn J., Koubský P., Ždárský F., Kříž S. (1979) Inf. Bull. Var. Stars #1689.
121. Peton A. (1974) Astrophys. Spa. Sci. 30, 481.
122. Percy J.R. (1979) Inf. Bull. Var, Stars #1530.
123. Percy J.R. (1981a) WPB, 227.
124. Percy J.R. (1981b) Inf. Bull. Var. Stars #1946.

125. Percy J.R. (1982) Astron.J. (in press).
126. Percy J.R., Lane M.C. (1977) Astron. J. 82, 353.
127. Percy J.R., Jakate S.M., Matthews J.M. (1981) Astron. J. 86, 53.
128. Poretti E. (1982) Inf. Bull. Var. Stars #2129.
129. Provin S.S. (1953) Astrophys. J. 118, 489.
130. Rachkovskaya T.M. (1975) Izv. Krym Astrophys. Obs. 53, 168.
131. Rachkovskaya T.M. (1976) Izv. Krym Astrophys. Obs. 55, 100.
132. Roach F.E. (1939) Astrophys. J. 89, 669.
133. Roark T.P. (1971) Astron. J. 76, 634.
134. Roark T.P., Baumert J.H., White N.M. (1972) Astrophys. Lett. 10, 55.
135. Schmidt H. (1959) Z. Astrophys. 48, 249.
136. Schuster W.J., Alvarez M. (1983) Publ. Astron. Soc. Pacific.
137. Sharov A.S., Lyuty B.M. (1972a) Inf. Bull Var. Stars #698.
138. Sharov A.S., Lyuty B.M. (1972b) Perem. Zvezdy 18, 377.
139. Sharov A.S., Lyuty B.M. (1973) Inf. Bull. Var. Stars #814.
140. Sharov A.S., Lyuty B.M. (1975) Astron. Cirkular 872, 1.
141. Sharov A.S., Lyuty B.M. (1976) Be 70, 105.
142. Sharov A.S., Lyuty B.M. (1977) Astron. Cirkular 956, 5.
143. Sharov A.S., Lyuty B.M. (1980) Astron. Cirkular 1119, 1.
144. Spear G.G., Mills J.Jr., Snedden S.A. (1981) Publ. Astron. Soc. Pacific 93, 460.
145. Stebbins J., Huffer C.M., Whitford A.E. (1940) Astrophys. J. 91, 20.
146. Stepinski T. (1980) Acta Astron. 30, 413.
147. Tempesti P., Patriarca R. (1976) Inf. Bull. Var. Stars #1164.
148. Turner D.G., Lyons R.W., Bolton C.T. (1978) Publ. Astron. Soc. Pacific 90, 285.
149. van Leeuwen F., Meys J.J.M., Alphenaar P. (1982) Inf. Bull. Var Stars #2173.
150. Walker M.F. (1953) Astrophys. J. 118, 481.
151. Walker M.F. (1958) Astron. J. 63 237.
152. Wallerstein G. (1963) Astrophys. J. 137, 280.

Subject list of references dealing with the photoelectric observations of Be stars

---

Individual references are identified by their current numbers in the list of references above.

1. Bibliography of Be stars

   85, 105, 106, 107, 118

2. Photoelectric observations obtained directly without comparison stars

   A. UBV data:

   21, 24, 25, 26, 28, 31, 36, 38, 39, 40, 41, 50, 55, 76, 86, 94, 103, 109, 114, 115, 147, 152

B. Other photometric systems:

1, 2, 3, 41, 42, 45, 46, 47, 71, 136, 145

3. Photoelectric observations obtained relative to comparison stars

A. UBV data:

9, 10, 17, 18, 19, 20, 22, 23, 27, 29, 31, 32, 34, 37, 43, 49, 57, 58, 59, 60, 73, 74, 80, 81, 82, 83, 84, 87, 88, 89, 90, 91, 93, 95, 100, 101, 104, 108, 116, 117, 121, 123, 125, 126, 128, 130, 131, 137, 138, 139, 140, 141, 142, 143, 148

B. Other photometric systems:

4, 5, 8, 48, 51, 52, 54, 75, 81, 96, 97, 98, 99, 110, 111, 112, 122, 123, 124, 125, 126, 127, 129, 132, 133, 135, 144, 149, 150, 151

4. Photoelectric observations of some particular Be stars

κ Cas HD 2905

9, 37, 75, 103, 124

RX Cas BD+67 244

60, 88, 93

ϕ Per HD 10516

32, 70, 97, 103, 127, 132, 136

BU Tau 28 Tau HD 23862

1, 2, 3, 32, 47, 60, 70, 80, 81, 136, 137, 138, 139, 140, 141, 142, 143, 149

λ Eri HD 33328

16, 97, 123, 126, 127, 136

HR 2142 HD 41335

38, 40, 41, 42, 97, 103, 123, 136

AX Mon HD 45910

27, 42, 48, 53, 70, 76, 97, 100, 103, 121, 136

28 CMa HD 56139

7, 8, 38, 39, 40, 41, 42

OT Gem HD 58050

22, 103, 128, 136

κ Dra HD 109387

1, 2, 3, 32, 103, 136

88 Her V744 Her HD 162732

1, 2, 3, 28, 34, 58, 60, 70, 101, 108, 136

CX Dra HD 174237

60, 65, 90, 91, 103, 104, 136

V1294 Aql HD 184279

2, 3, 31, 70, 83, 97, 103, 136, 147

V1507 Cyg HD 187399

60, 70, 75, 120

25 Cyg HD 189687

103, 123, 126, 127,

28 Cyg HD 191610

103, 123, 126, 127, 136, 144

P Cyg HD 193237

1, 2, 3, 48, 110, 111, 112, 136

EM Cep HD 208392

10, 23, 29, 75, 87, 89, 92, 97, 98, 103, 130, 131, 136

π Aqr HD 212571

40, 41, 42, 43, 54, 55, 70, 103, 113, 114, 115, 127

EW Lac HD 217050

1, 2, 3, 59, 60, 70, 96, 103, 123, 127, 150, 151

o And HD 217675

4, 5, 17, 18, 19, 20, 32, 33, 35, 48, 49, 51, 52, 60, 82, 84, 116, 117, 135

KX And HD 218393

1, 2, 3, 32, 57, 60, 70, 136

LQ And HD 224559

70, 103, 122, 123, 125, 126, 127, 129, 136

6

The 1982 - 1984 Epsilon Aurigae Eclipse Campaign

JEFFREY L. HOPKINS

Hopkins Phoenix Observatory
7812 West Clayton Drive
Phoenix, Arizona 85033

Small observatories have a unique opportunity to contribute significant data on an important world wide observing project. The Epsilon Aurigae star system has been studied from the early 1800's but still remains a mystery. The third magnitude system dims 0.8 magnitudes every 27.1 years. The ingress and egress last nearly 6 months each and totality over a year. During the 1982-1984 eclipse a concentrated effort is being made to determine just what the star system consists of. Observations are being made with spectroscopy, polarimetry, and photometry. Data are even being collected with the IUE satellite.

Because of the high brightness of the star system and the long period, large observatories have a difficult time observing the eclipse. The brightness tends to saturate the photometers used with the larger telescopes. Small telescopes, on the other hand, are ideally suited. Kevin Krisciunas has submitted data obtained with a 6 inch reflector, and typical work is being done with 8 to 16 inch instruments. Small observatories from over 20 countries are coordinating efforts to provide coverage of the eclipse. An Epsilon Aurigae Campaign Newsletter, published bi-monthly, keeps observers informed as to the status of the eclipse plus displays the data submitted.

Dr. Robert Stencel of NASA is coordinating the spectroscopy data collection and analysis, and I am coordinating the photometry data collection. There was a bit of excitment during the second contact in December 1982 when Jim Kemp of the University of Oregon reported some strange polarimetry observations. The parts of the Epsilon Aurigae puzzle are already beginning to fall into place. By the end of this eclipse there will be a much better understanding of the Epsilon Aurigae star system.

In Addition to the Epsilon Aurigae observations, efforts are being coordinated for observations of 31 and 32 Cygni and Zeta Aurigae. All the star systems are long period binaries. They are also bright and well within the capabilities of the small telescope. Plus they are badly in need of observations.

7

Photometry Among The Climatically Underprivileged*

J.D. FERNIE

David Dunlap Observatory
University of Toronto
Toronto, Canada

I. INTRODUCTION

Beginning in earnest around 1960, a remarkable revolution swept through observational optical astronomy, a revolution that will likely not be replaced until the advent of readily available telescopes in space.

I am referring to the practice of locating major telescopes at the best astronomical sites, regardless of how remote these might be. This practice had started much earlier, witness the "big" telescopes that were in California early this century, but two principal factors combined soon after mid-century to give great impetus to the trend. The first was the rapidly increasing technical sophistication of big telescopes, that concomitantly made them excessively expensive to build and to run. Cost effectiveness very soon became very important. At the same time, air travel was expanding enormously, so that problems in reaching remote areas became almost trivial - particularly the problem of travel time itself.

These factors (and others) soon led to the development of the great national and International observatories such as Kitt Peak National Observatory in Arizona and the European Southern Observatory in Chile. Very soon not only big telescopes were located at such sites, but whole flocks of lesser instruments as well, until some of these observatories became vast complexes of white domes.

The impact on astronomy has been incalculable. The efficiency and abilities of instruments in such sites have led to advances - particularly on very faint objects - that could not have been obtained anywhere else short of telescopes in space. This led rather naturally to the view, sometimes unconscious, sometimes not, that *all* worthwhile astronomy must come from such observatories; that observing in poorer climates is too inefficient and, in the case of photometry, too unreliable to be worthwhile.

**Reprinted with permission from the Journal of the Royal Astronomical Society of Canada, Vol. 76, p 224, 1982.*

I believe the time has come to reconsider this view. I offer two reasons, one practical and one scientific, although others could be added. On the practical side, we are now witnessing an enormous increase in travel costs. Travel costs to the David Dunlap Observatory's field station in Chile have more than tripled (almost quadrupled) in the decade of its operation, while individuals' research grants have done no such thing. One must now think quite carefully of costs before embarking on field trips to Chile. At the same time, running expenses have caused some super-site observatories to cut back quite drastically on at least their lesser facilities, so that competition for time on such instruments has become heavier than ever. Thus it is becoming more and more difficult to get observing time at good sites, and when time is obtained, it is exorbitantly expensive to take advantage of it. Under such circumstances local observatories, less efficient though they may be in their poor climates, take on renewed significance.

The scientific reason for reconsidering local observatories has to do with the kinds of scientific programs that are being undertaken in current research. If observing is restricted to visits at distant sites, the observer develops a rather definite pattern of work: he will likely have a few - perhaps only one or two - runs per year with the assignment of every night for maybe a week, depending on the size of and therefore competition for the telescope in question. On a 4-m telescope the run may be only a few nights. The brevity of these runs introduces an additional criterion for the kind of research to be undertaken: what will yield worthwhile (publishable!) results from a few consecutive nights of observing? (Some major observatories assign time partly with an eye to an applicant's previous publications record.) In the field of variable stars, for instance, one is more likely to bypass Mira stars in favor of β Cephei stars. Is the concentration of observing at good sites influencing the kind of work that we do? Are we missing some good research topics because they are less amenable to concentrated bursts of observing? At a local observatory, to which access can be had year-long, such problems do not arise.

I emphasize that there is no element of competition here, nor any implied denigration of super sites. What is done there can often only be done there. The question is whether, since not everything can be done at good sites, useful work cannot also be done at lesser sites. It will be different work, often less spectacular, but in the long run often no less valuable.

To show what can be obtained at a site that is climatically mediocre by world standards, this paper draws on actual results from the David Dunlap Observatory (DDO) in an area for which sky conditions are usually critical, viz. photoelectric photometry. Although this work is routinely done in five filters (UBVRI), discussion of mainly the V results will suffice to show that high precision photometry can be done on a useful number of nights at this observatory.

II. EQUIPMENT

It is important to emphasize that all the data discussed in this paper were obtained with a very simple, basic photometer mounted on a 0.5-m reflector that was built locally more than sixty years ago, and whose time-worn characteristics leave much to be desired.

An observation typically consists of one ten-second integration per filter (usually five in number: UBVRI) on star plus sky, followed by one ten-second integration per filter on sky alone. It is true that the signal is handled by expensive state-of-the-art photon counting electronics, but the point to be made is that the precision of the results reported here is *not* due to any elaborate sky-chopping photometer design or the use of an automated high slew-speed telescope.

This is not to say that significant improvements cannot be made through the use of such instruments. At this observatory we do use automated computer-controlled photometers too, and their advantages will be discussed in the final section of this chapter. But they are not essential for obtaining good results.

III. EXPECTATIONS

Photometry in a mediocre climate presents two problens. The first is the limited number of photometric nights in the year, a point I return to later. The second is the all-important problem of how to handle the atmospheric extinction corrections when they are liable to be variable in time and direction,and when the sky is liable to cloud over at any time.

The most famous remark in the literature of astronomical photometry was made by Stebbins and Whitford (1945): "... it is impractical to determine extinction thoroughly and accomplish anything else." This truism, echoed ruefully down the years by countless observers, makes an important point: whether one be observing at a good site, like Stebbins and Whitford, or at a poorer site, one's extinction corrections are at best approximations. The question is, how approximate can one's approximations be? The answer will depend on the actual extinction procedures being used.

The classic extinction procedure is to observe several stars of quite different colors over a change of at least one or two air masses, a procedure that in practice is usually reduced to observing two stars of different color twice: once at large air mass and once at small air mass. Even so, in my experience this procedure is almost useless for photometry at mediocre sites unless one is giving over one of the best nights of the year merely to determining extinction and transformation coefficients. The difficulty is mainly that it takes several hours to carry out the procedure, and all kinds of things can happen to the sky in that time.

An advance on the classic procedure is Hardie's method (Hardie 1959). Assume that the transformation coefficients have been determined already by using the classic procedure on one or a few nights. This means that one knows the quantities α, β, ζ, etc. in the equations which relate the standard system values V, (B-V), etc. to the instrumental system values v, (b-v), etc. For example,

$$V = v_o + \alpha(b - v)_o + \zeta$$

and

$$(B - V) = \beta(b - v)_o + \xi.$$

The subscript zero attached to instrumental quantities means that they have been corrected for extinction to outside atmosphere values. Thus for standard stars of known V, (B - V), etc., one can compute v_o , $(b - v)_o$, etc., and these are related to the observed values through the extinction equations. For example,

$$v_o = v - k_v X,$$

where k_v is the extinction coefficient in v and X is the air mass. Thus every observation of a standard star allows one to determine a value for k_v and examine its change with time and direction in the sky. (Hardie's method actually allows for slight zero-point shifts in ζ and ξ, caused by drifts in equipment sensitivity, by using pairs of standards at differing air mass, but the principle remains the same.) I have found Hardie's method a good one for work in modest climates, but it does involve additional reduction stages which, as we shall see, can be unnecessary.

A third technique for handling extinction is to substitute the extinction equations into the transformation equations so as to get a single set of equations of the form $V = f(v, b\text{-}v, k_v, X, \ldots)$. All standard star observations are combined and the equations solved by multilinear regression analysis. With the advent of computers, this approach is now much more feasible than it once was, and it has been recently refined and extended in an excellent way by Harris *et al* (1981). Its drawback for the poorer climate, however, is that usually no account is taken of the time- and direction-dependence of the extinction.

A fourth technique which also utilizes computing power is to allow the extinction coefficient to range over likely values, carry out the reductions for each value, and then choose that value which gives the best fit to the standard star observations. Although good results can be obtained with this method, its drawbacks are much the same as those of method three as described above.

I have experimented with all of these techniques from time to time, and have often been satisfied by them; but I have slowly come to abandon them in favor of yet another method: that of mean extinction coefficients.

The use of mean extinction coefficients (i.e. a set of values assumed constant for a given site, or perhaps with only a slow seasonal dependence) has a long record of good results at better sites, although it is not now much in favor. Stebbins and Whitford often resorted to it in their work at such sites as Mt. Wilson and Lick Observatories, and Hardie (1962) may be quoted: "It is usually found that a mean, based on a number of nights, is closer to the actual values than are the nightly averages themeselves..." This has also been my experience at Las Campanas, Chile.

However, while most photometrists might today grudgingly allow this for super sites, their eyes would surely widen in horror at the thought of using mean coefficients at a poor site. Yet it is my contention that the method can indeed be applied at such sites and will give results as good as any other, while also being the simplest to apply. I believe the data to be presented will bear this out.

The secret of success here, I think, and the reason why the technique is now feasible where once it was not, is that there is now a much greater number of standard stars available. Consider the UBVRI data published by Iriarte, *et al* (1965) for 1325 bright stars north of declination -50°. These are not standard stars in the strict sense of the term, but as we shall see are generally reliable to within 0.02 mag. Since they are fourth magnitude and brighter, they are roughly randomly distributed on the sky. A short calculation shows that the density of these stars on the sky is about 0.036 stars per square degree, which in turn means that there will be about 11 of them within 10° of any point on the sky. In other words, any star whose UBVRI data are to be determined can be expected to have about 11 other stars of known UBVRI values within 10° of it. It is these 11 stars that will provide the corrections needed to account for any error in the assumed extinction coefficients.

There is nothing special about 10°; it is just that stars within such a limited area will usually have very similar air masses, so that errors in the extinction coefficients will show up as nearly constant zeropoint errors in the magnitudes and colors. And, of course, all these stars are in the same direction and can be observed in a relatively short timespan, so that any dependence of extinction on these quantities can be removed.

As a specific case, consider an observer at this observatory, where the mean extinction coefficient in V is 0.23. The lowest value ever measured on any one night here (244 m above sea level) was 0.17. (Incidentally, the difference in k_v between the best nights at DDO and at Las Campanas, Chile, is almost entirely accounted for by Las Campanas being at ten times the altitude of DDO; there is only an additional 0.02 mag extinction at DDO due to added aerosol scattering.) There is no firm upper limit on k_v, of course, but I have very rarely found myself trying to work on a night when k_v exceeded 0.30. Thus virtually all photometry here is carried out at an extinction coefficient that is within ± 0.07 of the mean value. In fact, the observer is usually well able to judge whether he is in the upper or lower part of this range, so that his error is more likely to be ± 0.03, but I shall retain the ± 0.07 range for illustration.

At this latitude, routine photometry of any precision is not done much south of the celestial equator. Suppose the program star to be measured is on the equator at meridian passage. Its air mass will be 1.385. Suppose one standard star from which the zeropoint correction is to be determined is 10° further south. Its air mass will be 1.692. Finally, suppose the maximum error of 0.07 is present in the extinction coefficient. Then the error that will result from applying the standard star's zeropoint correction to the program star will be 0.07(1.692 - 1.385) = 0.021 mag. But if a second standard is taken 10° north of the program star, the error from it will be -0.013 mag, so that when the two standards are averaged, the net error becomes only 0.008 mag. If additional standards, say only 5° and east or west from the program star, are also averaged in, this net error will be reduced yet further. (The use of multiple 'standards' will also serve to reduce the errors resulting from any uncertainties in the published magnitudes of these stars themselves.

In practice, the above is a fairly extreme case. One is much more likely to be observing higher in the sky where air mass changes more slowly with declination, and the error in the extinction coefficient will usually be much less than 0.07 mag. Thus this simple analysis suggests that it should not be particularly difficult to achieve millimagnitude accuracies even in the relatively poor climate of the Toronto region.

We now turn to actual observations to see whether this expectation is borne out.

IV. RESULTS

I consider first the question of just how stable the Toronto-area sky is likely to be. Is there always a fluctuation in the transparency, and if so, of what frequency and amplitude? Table I presents a run of comparison star/variable star observations on two nights, each run covering about one hour. The numbers are just as they were printed out by the on-line computer, uncorrected for zeropoint or anything else. It is seen that for the September, 1979 set, the sky during this hour and for this direction was rock-steady at a level of about 0.002 mag. This, it must be admitted, was one of the best records ever achieved at DDO, and the data for October 1981 are much more typical. Even so, a precision of 0.005 to 0.010 is clearly achieved, especially if a small, smooth time trend is removed. This level of sky stability is not at all unusual, appearing on about three-quarters of the nights deemed photometric, and is not restricted to near-meridian observations; the October 1981 data were obtained at hour-angles between three and four hours. Furthermore, despite long experience in photometry, I often find that some of the most stable nights are those I had almost dismissed as non-photometric, i.e. the sky is often more stable (but not necessarily more transparent) than it looks.

If this is suspected of being biassed towards the better nights, consider Figure 1. I have gone back over my records for the last two years, and on *every* night during that period on which standard stars were observed, I have formed the residual between the

TABLE I

EXAMPLES OF SKY STABILITY

Sept. 4/5, 1979 Star	V	EST	Oct. 30/31, 1981 Star	V	EST
HR 8130	3.923	21:49	HR 6656	5.248	18:23
8157	6.134	21:55	HD 161796	7.316	18:28
8130	3.921	22:00	6656	5.254	18:34
8157	6.133	22:06	161796	7.310	18:39
8130	3.921	22:13	6656	5.261	18:46
8157	6.135	22:19	161796	7.312	18:51
8130	3.922	22:25	6656	5.269	18:57
8157	6.136	22:23	161796	7.315	19:02
8130	3.923	22:40	6656	5.269	19:08

TABLE II

SINGLE NIGHT ABSOLUTE PHOTOMETRY AT EQUATOR

Star	V	B-V	U-B	ε_V	ε_{B-V}	ε_{U-B}
HR 8781	2.488	-0.054	-0.071	0.00	0.01	-0.01
8717	4.905	-0.006	-0.001	0.00	0.01	0.00
HD 219150	7.201	0.386	-0.094			
8852	3.676	0.923	0.580	0.01	0.00	-0.01
219150	7.210	0.378	-0.096			
8852	3.695	0.915	0.552	-0.01	0.00	0.02
219150	7.203	0.375	-0.098			
8852	3.701	0.895	0.571	-0.01	0.02	0.00
8858	4.396	-0.142	-0.539	-0.01	-0.01	0.00
8911	4.930	0.043	-0.036	0.01	-0.01	0.00
8969	4.128	0.498	-0.003	0.00	0.01	0.00
8984	4.492	0.204	0.083	0.00	0.00	-0.01
9072	4.018	0.412		0.01	0.01	
219150	7.218	0.395	-0.118			

star's listed magnitude and the value obtained by me for that single observation. Extinction here has been handled by the use of mean coefficients as outlined in the previous section, stars having been grouped to form mean zeropoint corrections. On the best nights the group would consist of all the standards used throughout the night, on lesser nights grouping would be by time and direction. But no group had less than six stars from which to form the mean correction.

Figure 1 shows the frequency with which residuals of increasing size occur. The standard deviation of the distribution is $0^m.018$, which is to say that an absolute measurement can be made with an error less than this two-thirds of the time. Note that this refers to a single ten-second integration; repetitive measurements would of course improve the result. Note also that included in the figure are the errors in the published data; not all the error is to be ascribed to the observer. (But in fact, the standard deviation of $0^m.018$ including both observational and published errors, suggests that the data set of Iriarte *et al* (1965) is quite reliable on the average, even if the stars are not "standard" ones in the true sense.)

Record therefore shows that over many nights and seasons, absolute accuracies of order $0^m.01$ are routinely obtained, especially if measurements are repeated on more than one night. A specific example of this is shown is Table II, located on the preceeding page. These are observations made in the course of about an hour on one night to redetermine the magnitude and colors of the peculiar star HD 219150 (Fernie and Bolton 1980). The HR stars in the table serve as nearby standards, and HD 219150 is repeated several times to check on stability. These objects are close to the celestial equator (some are below it) so the situation is rather worse than average, and the night was by no means an extraordinarily good one. The three columns headed with ε show the corrections required to bring the observed values of the standards to their published values. The rms values of ε(V, B-V, U-B) for a single observation are $0^m.008$, $0^m.010$, and $0^m.009$; and these are the *external* errors. The internal errors, from the repeatibility of the HD 219150 measurements are $0^m.004$, $0^m.005$, and $0^m.005$. Clearly one can feel confident in having determined the magnitude and colors of HD 219150 to within $0^m.01$ despite this having been only an average night and having worked rather low in the sky.

Despite the good agreement and consistency revealed by Table II, one would like to know that these would be maintained if the star were observed on more that one night. Table III shows such a case for a star observed on a number of nights over two seasons. Evidently, consistency is not quite as good as one might have expected on the basis of Table II alone, particularly in the case of (U-B) - a color index notorious in this regard, but nevertheless the agreement is very satisfactory.

Strictly differential measurements are better. Table IV shows such observations of HD 219150 over three seasons. Precision of a few thousandths of a magnitude is generally achieved.

Finally, to show how well measurements at DDO can agree with those made at better sites, I offer Figure 2. This displays magnitude measurements of the cepheid variable SU Cygni made at DDO (closed) circles and by Moffett and Barnes (1980) at the McDonald,

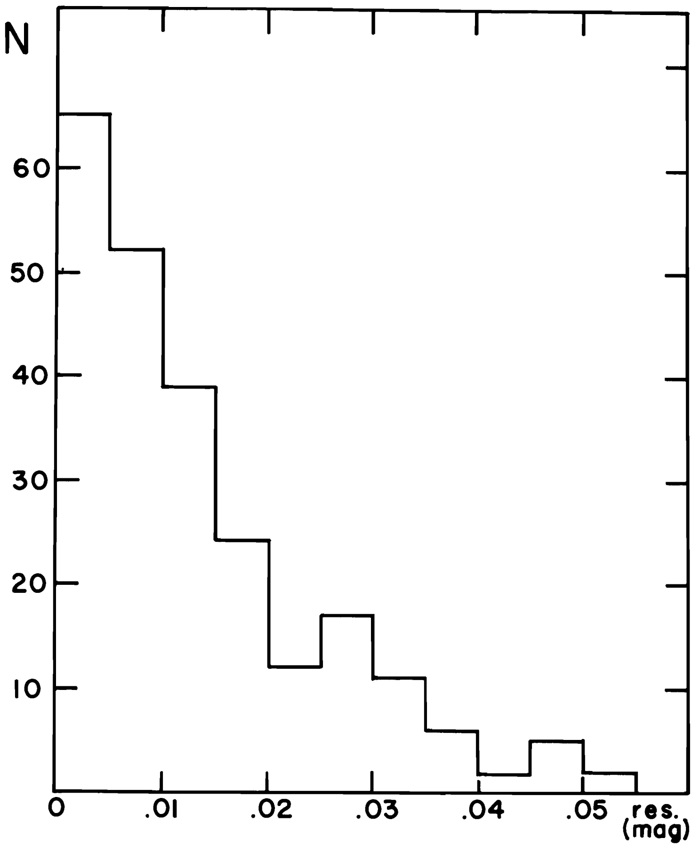


Fig. 1. Residuals in the observed V magnitudes of all standard stars observed at DDO over several years. These represent one observation per star and include the errors contained in the published data for the Iriarte *et al* (1965) "standards".

TABLE III

LONGTERM ABSOLUTE MEASURES OF HD 141532

DATE	V	B-V	U-B	V-R	V-I
June 11/12, 1979	7.482	0.417	-0.039	0.413	0.657
June 12/13	7.492	0.431	-0.028	0.392	0.631
June 18/19	7.480	0.443	-0.030	0.414	0.629
June 24/25	7.481	0.431	0.003	0.395	0.637
July 5/6	7.451	0.451	-0.006	0.404	0.674
June 11/12, 1980	7.486	0.434	0.019	0.409	0.644
June 20/21	7.480	0.441	-0.003	0.394	0.631

TABLE IV

LONGTERM DIFFERENTIAL MEASURES

	HD 219150 - HR 8852	
DATE	ΔB	ΔU
Sep. 17/18, 1979	2.990	2.306
Oct. 16/17	2.988	2.303
Dec. 17/18	2.986	2.308
Jan 3/4, 1980	2.988	2.302
Oct. 23/24	2.981	2.300
Sep. 23/24, 1981	2.984	2.311
Oct. 8/9	2.995	2.309

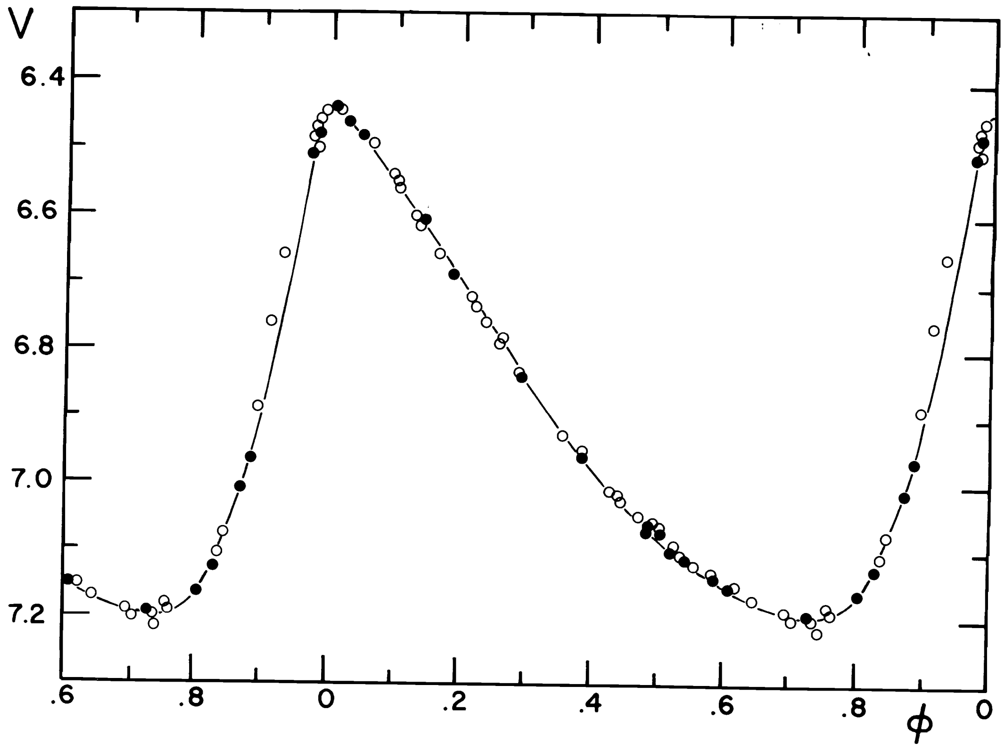


Fig. 2. Comparison of DDO magnitudes (filled circles) with those (open circles) of Moffett and Barnes (1980) obtained at a good site for the cepheid SU Cygni.

Table Mountain, and Kitt Peak Observatories (open circles). The DDO observations are listed elsewhere (Fernie 1979). No adjustment whatsoever has been made to either set of published magnitudes (although a correction of -0.016 has been made to the phases of the Moffett-Barnes data since their own published light curve clearly shows the peak offset from zero phase by this amount). The agreement is excellent.

The conclusion to be drawn from the data presented in this paper, it seems to me, is that absolute photometry can be and is routinely done in the DDO climate to an accuracy close to $0\overset{m}{.}01$, and that differential photometry can easily attain a precision of a few thousandths of a magnitude. Furthermore, these results are in accord with expectation if extinction is handled through the use of mean extinction coefficients and local standards. The belief that the climate is so poor as to make photometry not worthwhile finds no substantiation in fact.

V. HOW MANY NIGHTS A YEAR?

The super site zealot would doubtless demand a qualifying of the last sentence to the effect that while photometry is possible on some nights, these are so few as to make the overall effort not worthwhile. What, in fact, *is* the situation vis-a-vis the number of nights on which photometry can be done?

I have elsewhere (Fernie 1972) discussed ten years' of records and concluded that the Toronto area averages about 64 photometric nights (580 hours) a year. This, of course, hardly compares to the 2000 hours a year available at the best sites. Yet consider the case of an observer who is assigned two ten-day runs a year at say Kitt Peak for doing photometry on a small telescope. If his success rate is about 60 or 70 percent, he will accumulate around 150 hours of photometry in the year. A small telescope in a Toronto-like climate may well languish in relative neglect, and any one observer might easily obtain a quarter or a third of the available time for himself. In which case he will have as many or more hours of photometry in the year at home as he would have from Kitt Peak.

Nevertheless, any method by which the number of hours available for photometry could be increased is obviously worth exploring. For ground-based observations this means developing some kind of two-channel system, whereby one channel monitors a nearby standard star while the other in exact simultaneity observes the program star. Grauer and Bond (1981) have recently reported on such a system operating on one telescope with excellent results. At the DDO we hope to go one step further by using two nearby telescopes, which will enable us to use pairs of stars further apart of the sky (and so choose better matched pairs), and also enable us to chop between star and sky within each channel to remove rapidly changing sky brightness. Preliminary experiments, even with unmatched and unsuited photometers, have been extremely promising, giving differential measures constant to within $0\overset{m}{.}03$ while the output of any one channel varied by $2\overset{m}{.}2$. A newly designed system for this purpose is now under construction.

If two-channel systems of this sort can be made to give routinely successful results it will become possible to at least double the number of nights on which photometry can be done at DDO. While even then still not approaching conditions at a super site, the advantage of home operation combined with a reasonable number of nights a year will permit a great deal to be done.

ACKNOWLEDGEMENT

The equipment used for photometric work at the David Dunlap Observatory has been purchased in part through equipment and operating grants from the Natural Sciences and Engineering Research Council.

REFERENCES

Fernie, J.D. (1972) J. Roy. Astron. Soc. Can. 66, 249.
Fernie, J.D. (1979) Pub. Astron. Soc. Pacific 91, 67.
Fernie, J.D. and Bolton, C.T. (1980) Pub. Astron. Soc. Pacific 92, 328.
Grauer, A.D. and Bond, H.E. (1981) Pub. Astron. Soc. Pacific 93, 388.
Hardie, R. (1959) Astrophys. J. 130, 663.
Hardie, R. (1962) Astronomical Techniques (ed. W.A. Hiltner), chp.8, Univ. Chicago Press.
Harris, W.E., FitzGerald, M.P. and Reed, B.C. (1981) Pub. Astron. Soc. Pacific 93, 507.
Iriarte, B., Johnson, H.L., Mitchell, R.I. and Wisniewski, W.K. (1965) Sky & Telesc. 30, 21.
Moffett, T.J. and Barnes, T.G. (1980) Astrphys. J. Suppl. 44, 427.
Stebbins, J. and Whitford, A.E. (1945) Astrophys. J. 102, 318.

8

A FIBER-OPTIC FOUR CHANNEL PHOTOMETER

E. N. WALKER

Royal Greenwich Observatory
Herstmonceux Castle
Hailsham, East Sussex
England BN27 1RP

I. INTRODUCTION

The motivation for the instrument described in this chapter came from several years' work in the Spanish Sierra Nevada monitoring photometric changes in the optical counterpart of Cygnus X-1, and searching for Delta Scuti type variations in a variety of early type stars. A significant fraction of nights in the Sierra Nevada are non-photometric because of high, thin clouds or local transparency changes which are not visible to the eye as clouds, and yet result in brightness changes of several percent. The design criteria were to create a photometer capable of producing photon-statistics-limited results during conditions in which stars were visible, but when the sky would ordinarily be considered non-photometric. Although the instrument is still only available as a prototype, sufficient tests have been carried out, and the first scientific results have been obtained to demonstrate the potential of the concept. Many other observatories are situated where local conditions make photometry difficult, either because of haze and cloud conditions, or because of proximity to a town produces a bright and sometimes variable sky signal. We therefore describe our photometer in the hope that it will be of interest to other photometrists.

II. DESCRIPTION

Early in the project it was decided to use more than one comparison star. Previous experience had shown that when only two stars are observed, it is often clear that one is a variable, but much less clear which one. Two comparison stars were regarded as the minimum and three or more were better. Television type detectors suffer from the disadvantage that for reasonable field sizes, $\sim 1^{\circ}$, individual stars are so small that they cover only one pixel and it was therefore decided that a conventional photon counting photo-multiplier tube must be the detector. Fiber optics were used as the method of directing the light from the focal plane into the detector. A single photomultiplier tube, high voltage unit, etc. were used so that everything within the electronics package was compared with itself in the hope that stability could thus be ensured. The instrument comprises the following basic units 1) the focal plane positioners, 2) the chopper box and filter/photomultiplier unit, and 3) the microprocessor, which does all photon counting, calculates magnitude differences, and allows input/output communications for the observer.

A rectangular coordinate 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. At their innermost ends they are provided with an aperture to be centered upon each area of sky plus star. These apertures are easily changed and three sizes are available on the current prototype, providing fields of view on the 76cm Steavenson telescope of 1 arc min., 45 arc secs., and 32 arc secs. (see Figure 1). Underneath each aperture is a Fabry lens/prism assembly. This turns the light path through 90^{o} 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 fiber optic bundle. Each lens/prism/fiber 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 centering of each object in its respective aperture. This is done with the aid of a travelling microscope permanently mounted on XY slides positioned above those which carry the four arms (see Figure 2).

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

When the project was started it was not known what changes in transmission efficiencies would result from the fiber optics moving or drooping as the telescope moved. It was therefore decided that a calibration must be carried out (the equivalent of "flat fielding" with contempory detectors) so that the signal in each of the four channels could be normalized. Experience has shown that changes of a few percent are typical and 10% is possible. Therefore once the objects have been centered and the light deflected into the fiber bundles, the calibration is carried out. This is done by simply 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 normalize all channels for all further observations until such time as the procedure is repeated. The signals are then carried by the fiber optics to the chopper box.

The four incoming fiber bundles, each with an active diameter of 2mm, are plugged into the front of the chopper unit. 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 fiber bundle which is one arm of a 4 into one fiber optic integrator which leads to a common 6mm diameter output. The distance between the 2mm diameter in-

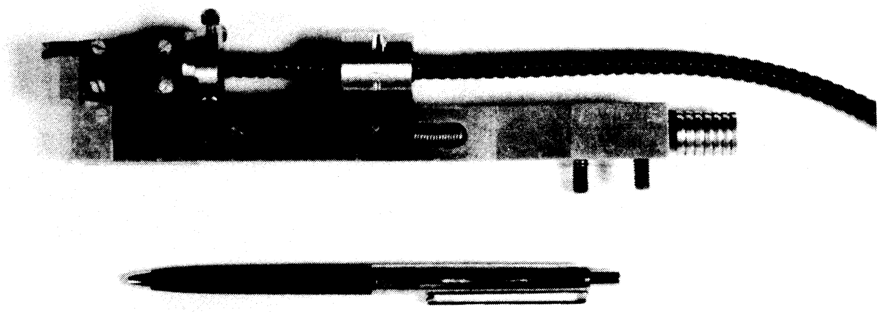


Fig. 1. Side view of one of the four arms which carry the apertures. lenses, and fiber optics to the focal plane.

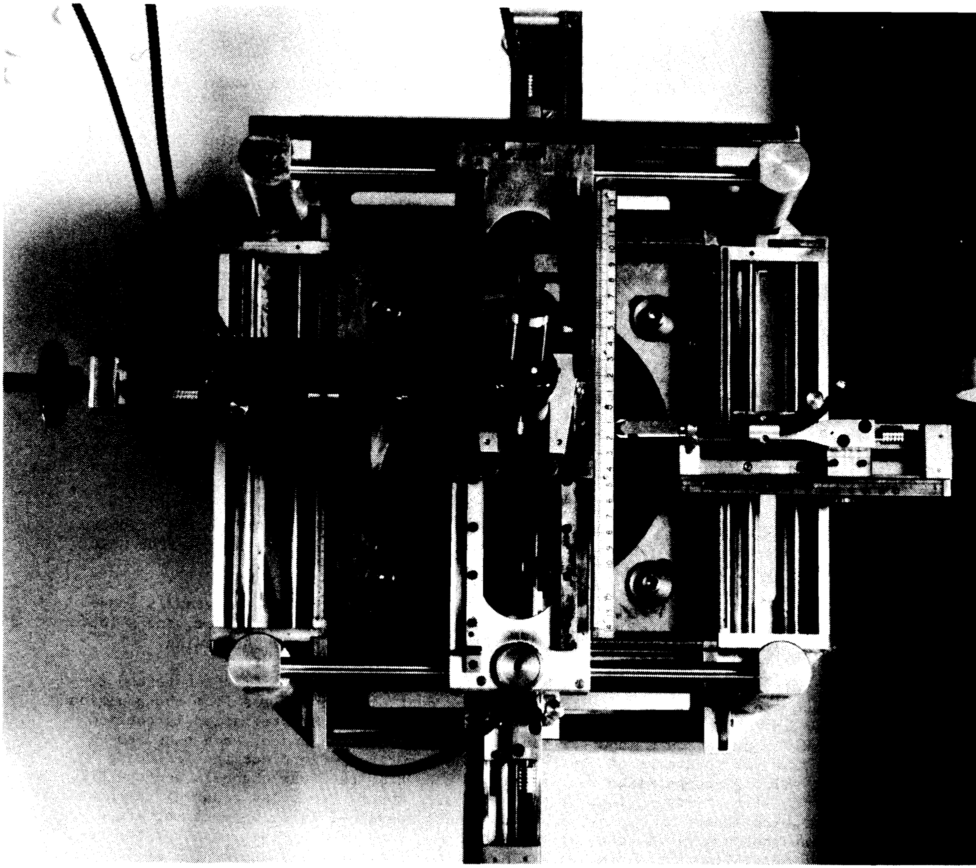


Fig. 2. The four XY-arm assembly for positioning the apertures in the focal plane.

put 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 82° cut-out slot. On one radius it contains a single hole, and on another radius it contains 4 holes. In combination with opto switches, these 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: 1) not wanting to chop too quickly and perhaps running into scintillation effects, and 2) not wanting to use any simple subharmonic of 50 Hz, which is the electrical mains frequency throughout Europe. No claims are made that this chopping frequency is optimized, but in practice it appears satisfactory.

The light which emerges from the 6mm diameter common end of the 4-into-1 fiber optic integrator emerges at an angle of approximately one radian. In order to produce a scrambled image on the photocathode and to provide a more parallel beam in which narrow band filters can be used, a Fabry lens system collects the light from this common end. This consists of two f/0.8 lenses, each consisting of two plano convex lenses with 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 with a Princeton Applied Research preamplifier/discriminator unit bolted to the outside. See Figure 3.

A Motorola 6800 microprocessor unit is used 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/discriminater 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 6-second integration time (25 rotations of the chopper) 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 was used which looked at the sky only, 3) 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, and 5) the magnitude differences between the first channel and the other three (or two if a sky channel was used) and the secant of Z for the middle of the integration. The chart recorder records Sec Z corrected magnitudes in channel one, which are 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

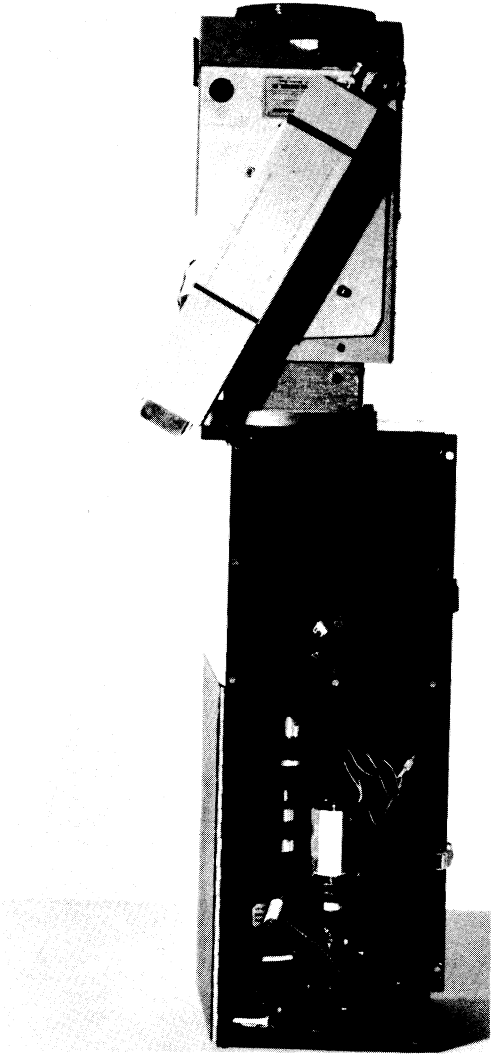


Fig. 3. The open Chopper Box showing the 4-into-1 fiber-optic adaptor, the motor which drives the chopper with its flexible drive, the P.F.R. cooler, and the P.A.R. preamplifier/discriminator.

channel was used. These are updated every six seconds for the chart recorder only.

III. RESULTS

We will demonstrate below, three aspects of the instrument'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 4 shows a 5 hour run on the eclipsing Wolf Rayet star CQ Cephei. The V magnitude of this star is about $9^{m}.2$. The results were obtained through a narrow (F.W.H.M. 100 Å) filter centered on λ = 5300Å, and through a maximum of $1^{m}.3$ of extinction, resulting in an equivalent magnitude through a broad band filter of $11^{m}.5 - 12^{m}.5$. The observations were obtained on the 76cm Steavenson telescope in the 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, $m_v = 8^{m}.7$) used by Hiltner (1950) as a comparison star, and CQ Cep - HD 214220 (AO, $m_v = 8^{m}.8$). Finally, at the bottom of the figure we show this same mean magnitude difference again, but this time with the vertical scale amplified by 10 in order to show details. The eclipse is clearly visible and the time of the center can be determined to within a few minutes. We believe that this demonstrates the ability of this instrument to produce results on fairly faint stars ($\sim 12m_v$), 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 photometer's ability during variable cloud cover is in Figure 5. 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 5 we show the magnitude of η Cyg - HDE226868. This changed by $\sim 0^{m}.05$, while the signal from η Cyg fell by about 6 mags. We are not claiming that the machine will work properly through 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 behavior 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 6 shows the blue magnitudes of HDE226868 relative to η Cyg on 12 nights during one lunation in 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

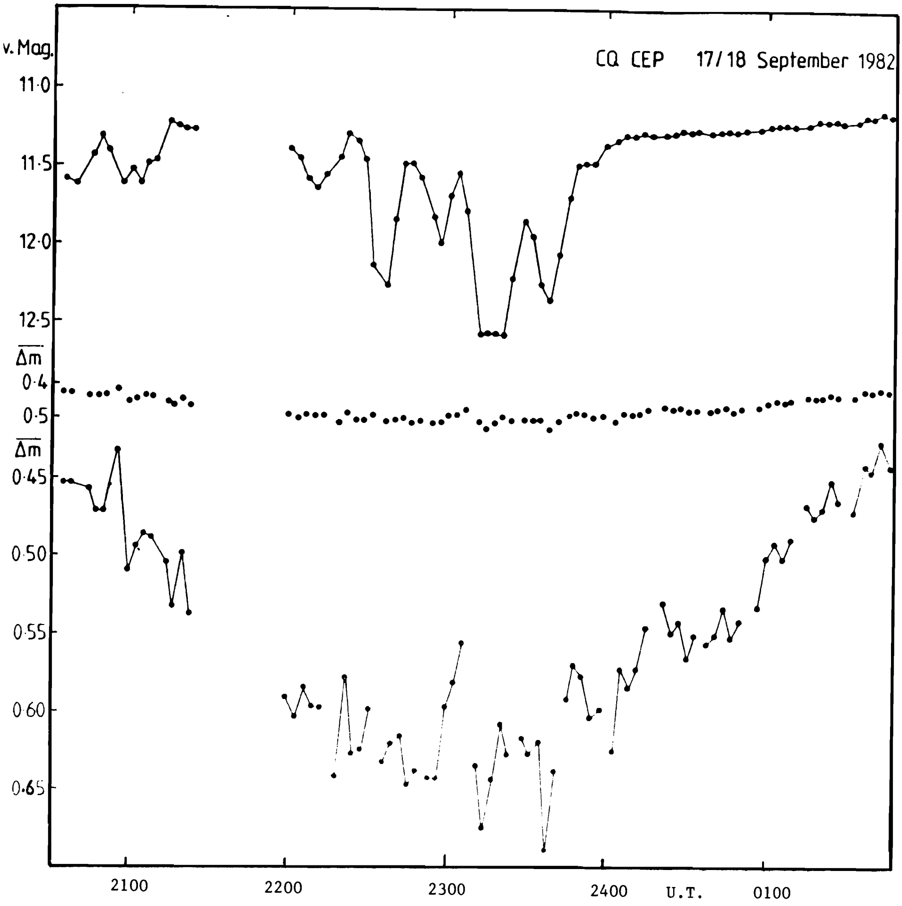


Fig. 4. The upper diagram shows the variations in apparent brightness of CQ Cep due to transmission changes in the sky plus changes intrinsic to the star. The middle plot shows the difference between CQ Cep and two comparison stars (HD214259 and HD214220) on the same scale as the upper plot. The bottom curve repeats the data in the center plot but with the vertical scale increased by 10 to show the details.

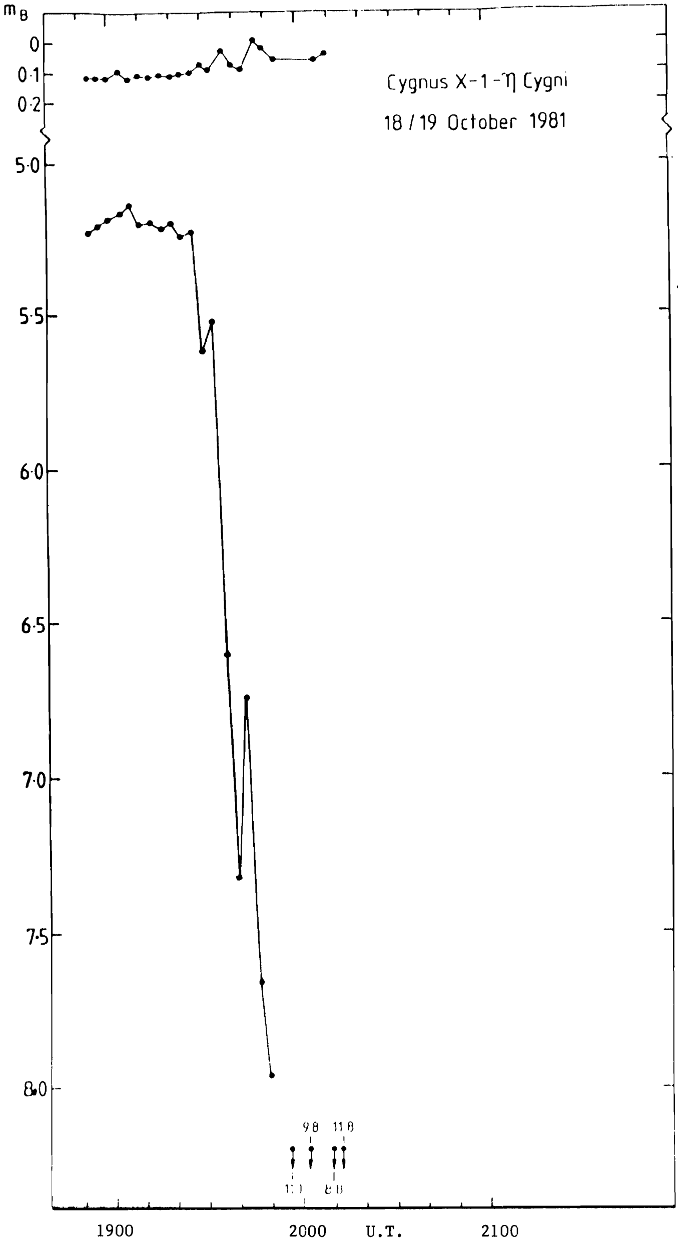


Fig. 5. The lower curve shows the change in apparent brightness for η Cyg as the sky became cloud covered. The upper data shows the change in magnitude between η Cyg and HDE226868 (Cyg X -1) over the same time interval.

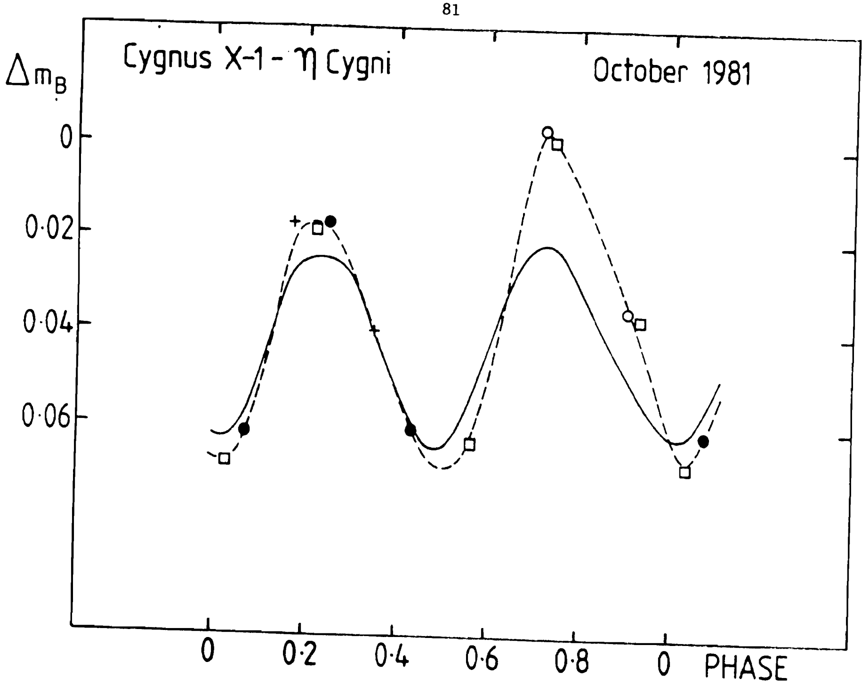


Fig. 6. The solid line shows the mean light curve of HDE226868 (Cyg X-1) derived from 9 year's data. The dashed line is a hand drawn fit to 12 nights of data obtained through one lunation in October 1981. Different symbols represent data from different 5.6 day orbits. The data were obtained in a variety of conditions from cloudy to clear, and from bright moonlight to no moonlight.

the light curve of this optical counterpart of Cygnus X-1 is variable with time and therefore the different amplitudes 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 around it is small ($\sim 0^{m}.002$).

Finally, we wish to show the performance of the instrument under good sky conditions. In Figure 7 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 7 we show the signal for 92 Tau without any Sec Z correction. Beneath it we show the magnitude differences between 92 Tau - 89 Tau, and 92 Tau - 91 Tau. The variation of $\sim 0\overset{m}{.}07$ in 2½ hours is clearly visible in both plots.

Figure 8 shows a 5 hour run on HR8752 (G0Ia , $m_v = 4.9$) compared with HD217673 (K2, $m_v = 6.2$) and HD217127 (A0, $m_v = 7.7$). The upper curve shows the steady trend downwards of HR8752 until the star was 4½ hours past the meridian (sec Z = 1.47) where there was a sudden increase in the extinction coefficient. The lower curve shows the mean magnitude difference from the two fainter stars. The scatter lies within the $\pm 0\overset{m}{.}01$ range. This is larger than would be expected from photon statistics alone and will be discussed later.

We believe that these results show the inherent capabilities of the concept and that anyone else desiring to do photometry in less than optimum conditions could, with advantage, use the principles descrubed here.

The quantum efficiency (Q.E. ≃1%) of this photometer seems to compare unfavorably with that of a conventional photometer (Q.E. ~20%). However, it is unrealistic to compare the efficiency of a single channel of this four channel instrument with a single channel instrument. Rather, the comparison should be with a single channel photometer being used to monitor a variable, two comparisons, and the sky. First centered on one star, the telescope is moved to a second star and centered, photon counting started, etc., and the whole cycle being repeated for four fields. When this is done and the telescope dead time taken into account, then the new photometer is not seriously less efficient. This has to also be set against the fact that results are attainable during less than perfect conditions, whereas with a conventional photometer no results would be obtained.

The light losses can be accounted for by a factor of 5 for chopping losses, i.e. one channel counting at a time and dead time due to switching, 2 lots of 60% efficiency in the fiber optic bundles due to end losses and packing fraction lossed and sisteen air/glass or glass/air interfaces which in the prototype are not optically cemented to allow interchange of components as development continues. A final version of the instrument using fluid light guides to replace the first fiber bundles and optically cementing approximately half of the components in the light path would possibly be a factor of 2-3 more efficient. If the choice was made to use four sets of detecting electronics then efficiencies within a factor of 2 of a conventional photometer seems possible. Lack of dead time due to changing the telescopes position might will result in a highter overall efficiency than a conventional telescope/photometer combination.

IV. LIMITATIONS AND PROBLEMS

The purpose of this section is to help those who might wish to make a similar device. Some difficulties have been overcome, some remain to be solved. It is more efficient for others to learn from the author's mistakes than to copy them. Space precludes an exhaustive discussion of all problems encountered, but the author will be pleased to answer any queries directed to him.

The present photometer is designed to work with a 20cm diameter field of view. This is 1 degree on the Steavenson telescope. Comparison stars must therefore be within this distance of the variable star of interest. Certainly there are times when a larger field would be better. In practice the most common limitation imposed by this is that stars used by previous workers as comparison stars are outside this field size. In addition, the brighter the star of interest the less likely it is that a star of similar color and

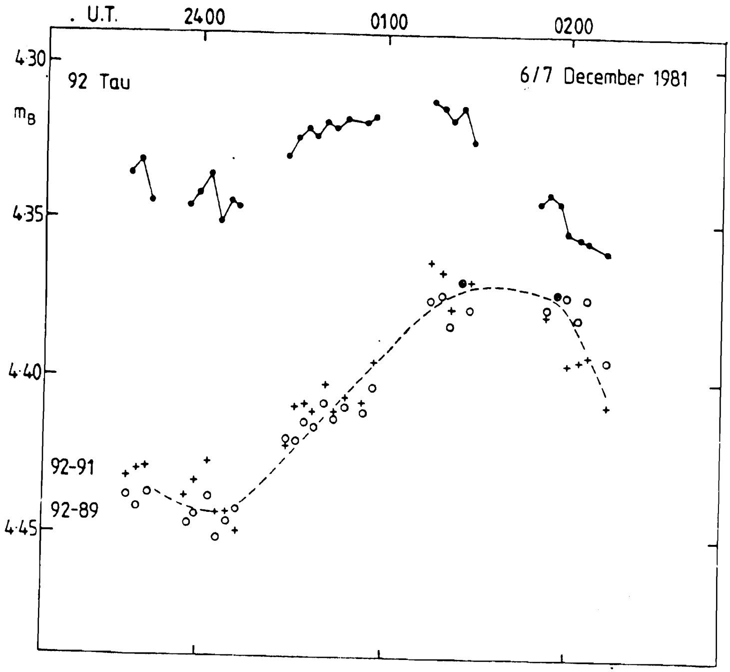


Fig. 7. The upper curve shows the change in apparent brightness for 92 Tauri over 2½ hours, which was due to intrinsic changes in the star and Sec Z effects. Below we show the differences in magnitude between 92 Tau and 91 Tau, and between 92 Tau and 89 Tau. These show the $\sim 0^m.07$ change in 92 Tau during the observations.

magnitude will lie within 1^{o}. Comparison stars therefore typically have to be fainter than the star to be investigated. Galactic latitude or cluster membership influences the number of stars of given brightness likely to be found within a 1^{o} field, but so far no star under investigation has had to be rejected because of lack of suitable comparison stars.

One of the design criteria was that the photometer should be able to work in the ultraviolet. At the time of construction the only supplier of UV fiber optics in Europe was Schott, and their 2mm diameter bundles were chosen. These are manufactured on a "one off" basis and are subject to greater or smaller irregularities in the packing of the individual fibers. In addition, it is impossible to obtain coherent bundles so that the Fabry image on the input end is totally scrambled on the output. This causes difficulties in optical alignment. Originally a 1.9mm diameter image was put onto the 2mm diameter fiber optic bundle. In practice this proved overly critical and the Fabry image was reduced to 1.7mm diameter. This image now only impinges upon about 180 of the individual fibers as opposed to the larger number available in the whole bundle. The inhomogeniety of the packing and occasional dead fibers mean that image wander of 50 μ or greater can cause variations in the transmission efficiency. If this occurs on a time scale which is short when compared with the time between calibrations, then this is a potential source of the $\sim$1% variation visible in Figure 5. An analysis of the results obtained on bright stars before and after the change from 1.9mm diameter Fabry image to a 1.7mm diameter one shows that σ changed from 5.5 millimags to 6.8 millimags; a ratio $\frac{5.5}{6.8} = 0.809$. The Fabry image ratio is $\frac{(1.7)^2}{(1.9)^2} = 0.801$. The agreement of those two ratios strongly suggests that the size of the Fabry image and the number of individual fibers used is causing these stochastic variations.

The Fabry lens system is inadequately designed to take the light from the common end of the fiber optic 4-into-1 integrator, scramble it, and place it upon the photocathode. The image is not sufficiently homogeneous in practice, and different points of the photocathode are illuminated by different channels. In addition, spherical aberration caused by the lenses themselves (f/0.8) is sufficiently large to make the size of the image upon the photocathode critically large compared with the photocathode size, and hence sensitive to any flexure which occurs as the telescope rotates.

V. THE FUTURE

The present prototype is probably only capable of improvement in two areas. One is to replace the fiber bundles by fluid filled light guides which have recently become available. This should reduce any variations due to image wander on the irregularly packed fiber bundles. The second area of improvement would be to more effectively scramble/homogenize the output from the 4-into-1 fiber optic integrator. Modifications are underway to effect improvements in both these areas.

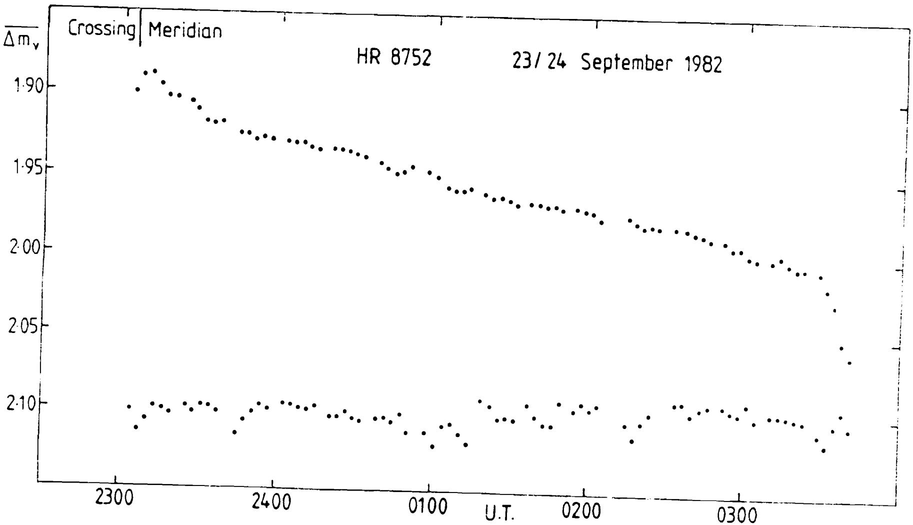


Fig. 8. The upper line shows data of HR8752 obtained through a Johnson V filter for 4½ hours after meridian crossing. The change in apparent brightness is due to increasing Sec Z until finally the extinction coefficient started to increase rapidly. The lower data show the mean differences between HR8752 and two comparison stars, HD 217673 and HD 217127.

The organizers of the French project to place a telescope at the south pole for continuous monitoring of variable stars have decided to use an updated version of the present instrument. This will have more sophisticated positioning of arms in the focal plane and will use four photomultiplier tubes to remove chopping losses. In the more distant future the logical development of the instrument would be to use computer controlled positioning of the 4 XY arms in the focal plane for rapid acquisitioning of the stars, fluid light guides, and a CCD chip as the detector. This would remove all chopping losses and can have a higher quantum efficiency than photocathodes. In addition, the use of a coherent fiber bundle to bring the image of a guide star to the CCD will allow the same detector to control all acquisitioning and guiding. This means that the whole instrument package can be reduced to the size of the focal plane positioner only. Mechanical design for such a photometer is completed.

VI. ACKNOWLEDGEMENTS

The development of any instrument such as that described here is very much the result of efforts of many people posessing a wide range of skills. It is therefore a real pleasure to thank Ian van Breda, Neil Parker, and Phil Rudd for providing the entire electronics/software package. Bill Crump and Carl West drafted the designs, and the mechanical expertise of Dennis Hartley turned the designs into metallic reality.

9

DESIGN AND USE OF A COMPUTER-BASED PHOTON COUNTING SYSTEM

RICHARD H. STANTON

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

I. INTRODUCTION

A professional-level astronomical photometer can be built by combining a personal computer with a "home-brew" photon counter. This description is written to pass on some of the author's designs and experiences with such a system. The beginner may find the electronics and software described to be somewhat overwhelming. But perserverance in mastering this technology will provide him with a powerful, state-of-the-art measurement system and a tool for original scientific work. It should be pointed out that the computer used (North Star Horizon) was selected in 1978 based on the technology available at that time. Today, similar results may be achieved using substantially less expensive computers using the counter/timer described in Section III.

Two important implementation decisions are made at the outset: (1) that the photometer is based on photon counting rather than an analog approach (Stanton 1981b), and (2) that all data acquisition, processing, and display will require the use of a computer.

Without getting into all of the pros and cons of these choices, both can be recommended as the preferred approach to astronomical photometry. Since light arrives as individual photon events (although it also has wave properties), the best one can ever do in measuring light intensity is to count these events. Despite what may appear at first glance to be complicated circuits, a counting system is in many ways simpler to build and use than its analog counterpart.

Once the decision for photon counting is made, raw output data assumes the form of integer numbers (counts per interval). These numbers can be readily gathered and stored by a small computer, and serve as the data set for later analysis and display. Thus the observer is not only freed (by photon counting) from making numerous gain adjustments at the telescope, but he no longer has to worry about reading meters or digital readouts during an observation. These mundane considerations, while easily ignored during the design phase, can become the predominant factors determining the usefulness of the finished photometer system.

The observing examples furnished in Section V by no means exhaust the possibilities for this system. Rather, they are described as limiting cases in the time domain: street lights and occultations, vary on the scale of milliseconds, while comparison stars for variables don't vary at all (hopefully!).

II. SYSTEM DESCRIPTION

A complete photometric system must have the capability to (1) gather and store raw data (photon counts per interval) and (2) process the raw data into corrected magnitudes. A block diagram of the overall system is shown in Figure 1. Pulses from individual photoelectrons (multiplied by approximately 10^6 in the photomultiplier dynode chain) are detected by the amplifier/discriminator. Once a photon is detected, the amplifier/discriminator produces a standard digital pulse which is the same regardless of the size of the input pulse. Figure 2 shows typical pulses from the photomultiplier tube. Note that they are of relatively small amplitude (a few millivolts) and of negative polarity. Due to the scope trigger setting, the large variation of pulse amplitude is not apparent in this photo. Figure 3 shows the amplifier/discriminator output pulse. Note that the amplitude is now over 2.5 volts and all pulses are positive and identical.

PMT and Photometer Head

Although I shall concentrate on the counting and processing of these pulses, a few words should be said about the photomultiplier, amplifier/discriminator, and photometer head. I use an EMI 9789B end-on photomultiplier operating uncooled. It was selected for low dark count rate, but the extra expense for this selection was probably not warranted. On a typical night ($\sim 40^{\circ}$F) dark current is so low (~ 4 counts/s) that its contribution to measurement noise is insignificant. A factor of five increase in this parameter could be easily tolerated.

The mechanical layout with this tube is shown in Figure 4. It is a straight-through design without optical folding. Both previewing and postviewing eyepieces are provided (a *must* for sanity while observing). Linear slides containing 5 diaphrams and three filters (or two and clear) are positioned in the optical path with controls which can be easily accessed in the dark. The configuration has proved very workable in conjunction with a 16-inch Cassagrain telescope (Figure 5) since a 90° fold is already required for viewing in most directions. Filters are changed manually, an approach that has worked well since they can easily be moved without disturbing telescope pointing.

For long periods of continuous observation, the first flip mirror is replaced by an

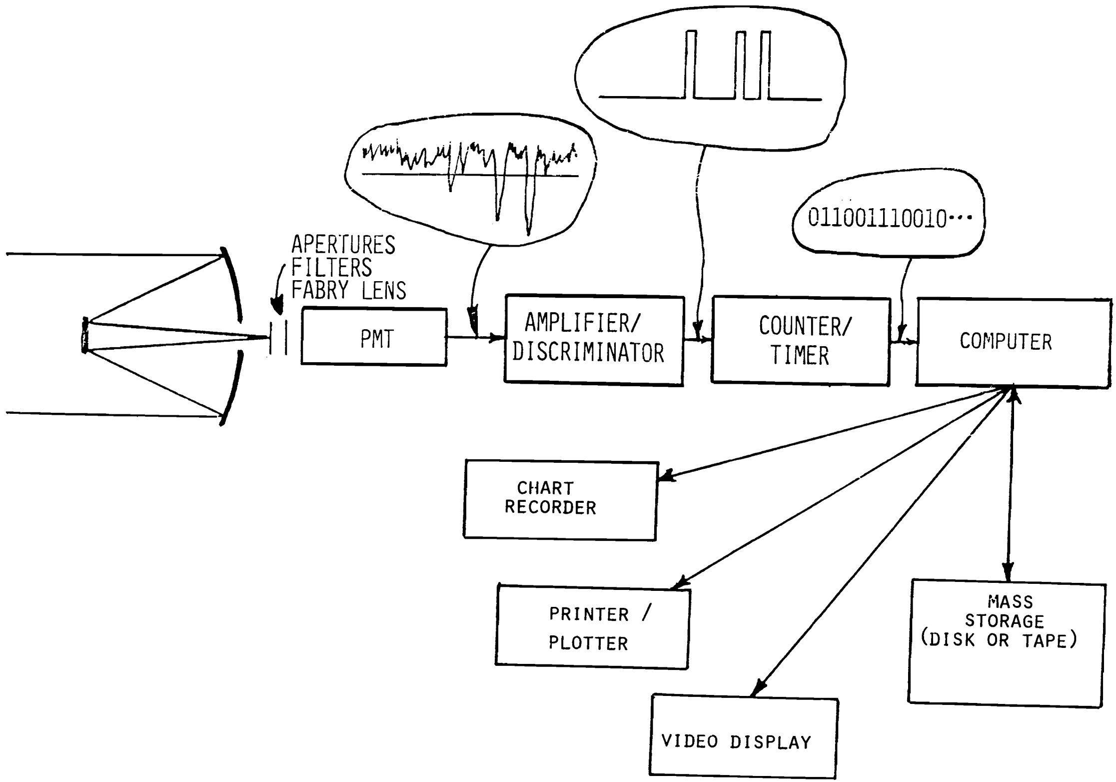
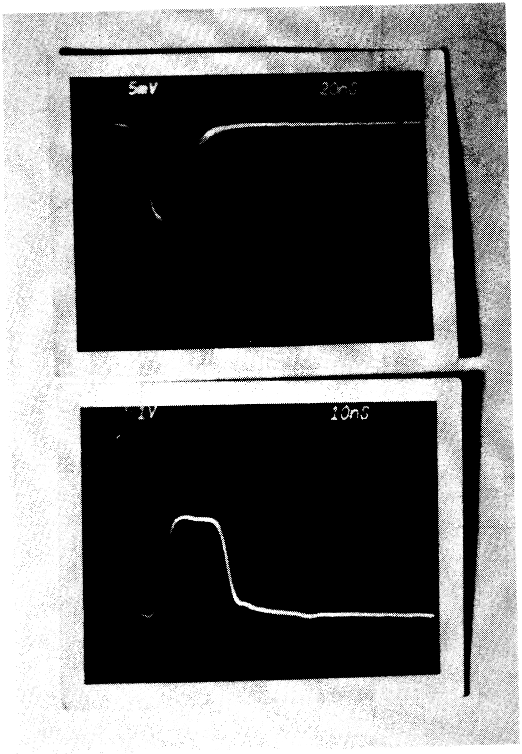


Fig. 1. Block diagram of author's system illustrating schematically the signals present at each point. Note that by only counting pulses larger than a fixed threshold, most of the noise is eliminated.



TOP: Fig. 2. Typical single photon output pulses from the photomultiplier. The trace is blurry since it is composed of many overlapping pulses of varying amplitude.

BOTTOM: Fig. 3. Whenever a photon pulse is detected, the amplifier/discriminator produces the TTL-level pulse.

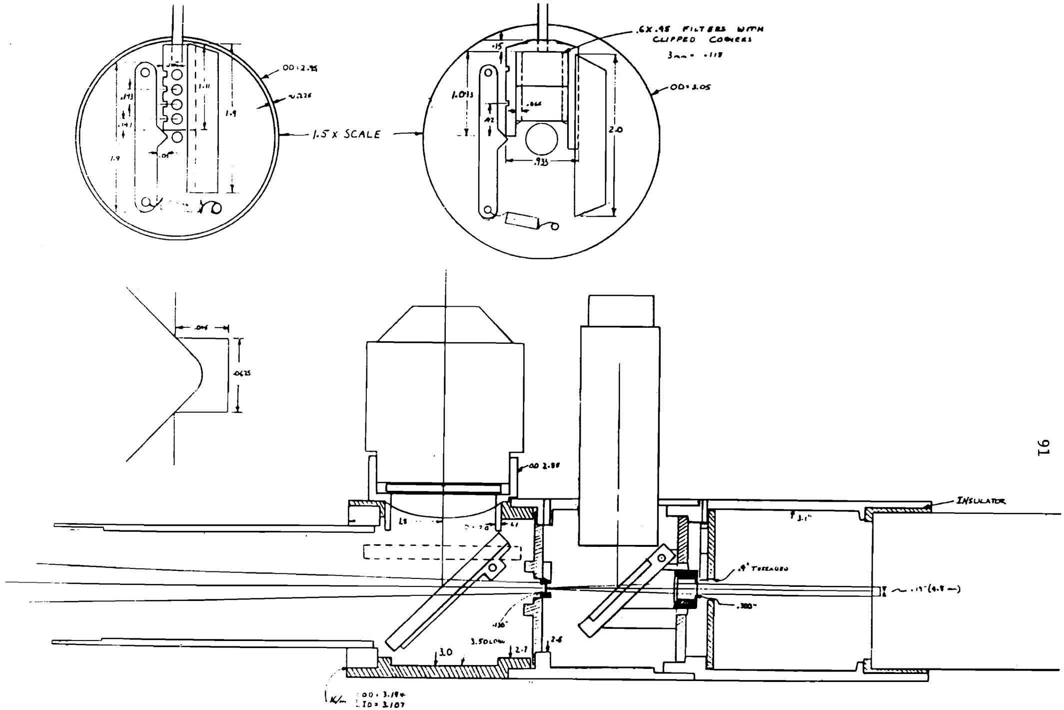


Fig. 4. Mechanical layout of the photometer head with detail drawings of aperture and filter slides.

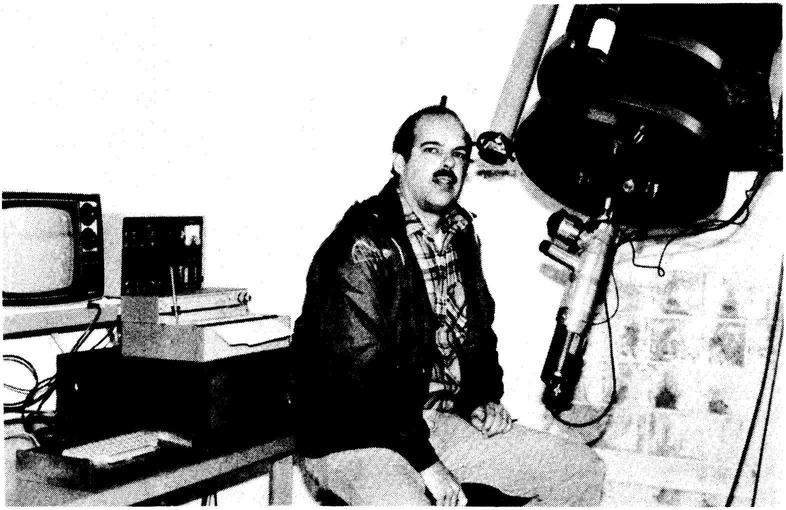


Fig. 5. Photograph of the entire system installed on the author's 16-inch telescope. The amplifier/discriminator is contained in a small box mounted just under the phototube. Cables (25' long) for high voltage, photon pulses, and discriminator power are routed across the floor to the telescope pier.

unaluminized cover glass. While most of a star's light is transmitted to the PMT, approximately four percent, per surface, is reflected into the previewing eyepiece where it can be tracked. This "poor man's" substitute to offset guiding has worked well as long as the star is at least three magnitudes brighter than the telescope's threshold. For fainter stars, there is no substitute for an accurate polar axis alignment and a good clock drive.

Amplifier/Discriminator

The amplifier/discriminator, mounted very close to the PMT output, was made by a now defunct company on Long Island. Fortunately, an equivalent (and cheaper) unit can be made using the LeCroy MVL-100 integrated circuit. A design using this chip has been described

(DuPuy 1981), as have been a number of high voltage power supply designs (Hall and Genet 1982). Although these elements are important to any photon counting system, they are adequately covered in these references and their design will not be discussed here.

Before leaving the amplifier/discriminator completely, a word should be said about noise interference for this device. It is often said that susceptibility to radio-frequency (RF) interference is one of the major drawbacks of the photon counting technique. While the circuits involved are quite sensitive to interference (due to the amplifier's high gain and frequency response), proper design can eliminate the influence of external RF sources. With adequate shielding of the input and output signals, a tight metallic enclosure, and feed-through filtering of the power supplied to amplifier/discriminator, a device capable of trouble-free operation in virtually all RF environments can be achieved. This was convincingly demonstrated when this system operated, without any degradation, at the Mount Wilson Observatory, a few hundred yards from most of the TV and radio transmitters for Los Angeles.

Counter/Timer

Brightness information coming from the amplifier/discriminator is completely defined by the *rate* at which photon pulses arrive. Since it is impractical for the computer to count each pulse, supplemental digital circuits must be fabricated to (1) generate precise timing intervals, (2) count the number of photon events in each interval, and (3) communicate the total counts to the computer at the end of each interval. The computer then stores the total counts per interval, in binary form, for later processing. By subsequently storing this raw count data on floppy disk (or magnetic tape) the observer retains a complete and detailed record of the night's observations.

The timer automatically resets the counter at the end of each interval, so a continuous record of the photon rate (brightness) is stored. The *time resolution* of the stored data is determined by the integration period set by the observer. For very fast events such as occultations, the number of counts is recorded every millisecond. For most variable star work, a count interval of between one and five seconds is used.

Data Acquisition and Real-time Display

Figure 6 illustrates the flow of the data acquisition process including hardware (counter/timer) and software (data acquisition) functions. Once parameters are initialized, the counter/timer chain operates in a continuous loop by counting pulses for the desired integration period (T_0), latching the count for computer readout, resetting the counters, and starting the next integration. When each integration is completed, the computer is interrupted to indicate that a fresh count word is available for storage. Since the dead-time between integrations is less than one microsecond, less than 0.1 percent of the discriminator output pulses are lost, even for T_0 as short as one millisecond.

The right side of Figure 6 illustrates the software activities which occur in parallel with the counter/timer functions. Since the retrieval of photon data is interrupt driven, the computer can be operating any program when not servicing the interrupt. In

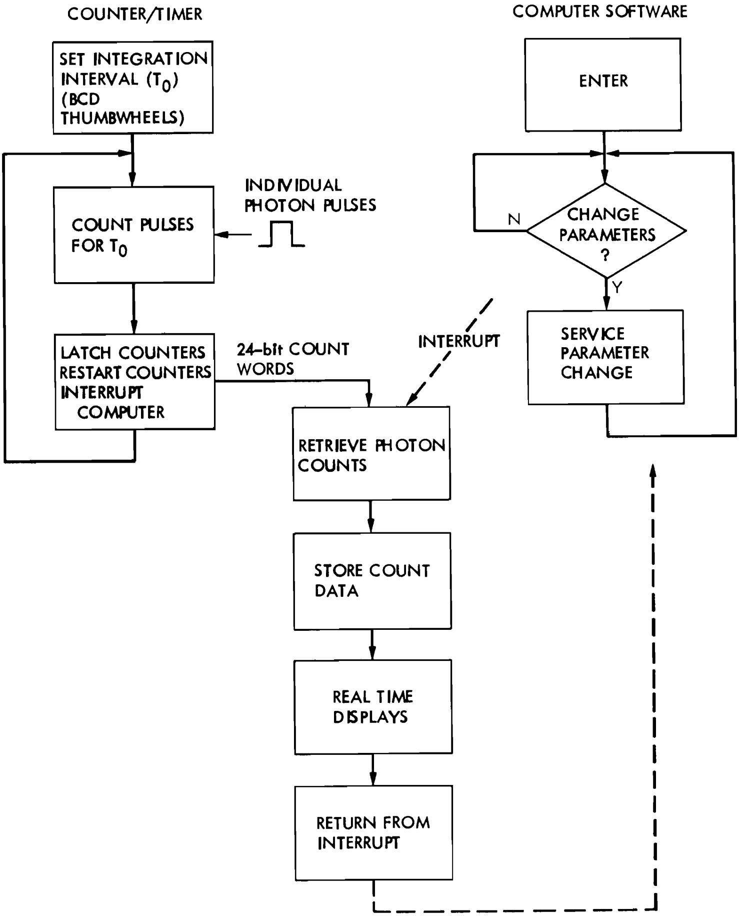


Fig. 6. Hardware/software functional flow.

practice, limitations in the observer's ability (particularly at 3 a.m.!) restrict the amount of parallel activity. For most observations, the processor continually polls the keyboard for changes in the software operating parameters while waiting to be interrupted. In this way, changes can be incorporated into the operation without stopping the data acquisition process. Typical software commands are listed in Table 1.

Table 1: Typical Real Time Commands

Key Pressed	Function
RETURN	Interrupts disabled; control returned to Executive
CNT-E*	Interrupts enabled
CNT-P	Data pointer initialized
CNT-T	Toggle real-time video display
CNT-K	Toggle real-time chart recorder output
CNT-R	Restart at beginning when memory filled
CNT-S	Stop when memory filled
U	Increase scale of video plot by 2x
D	Decrease scale of video plot by 2x
Y	Increase scale of chart recorder output by 2x
N	Decrease scale of chart recorder output by 2x

*CNT = CONTROL key depressed simultaneously with indicated letter

When an interrupt from the counter/timer is received, the microprocessor calls to the interrupt processing routine to retrieve and store the count data (3 bytes). In addition to gathering and storing the count data, several real-time displays can be provided by the computer (comtrolled by the keyboard):

(1) Decimal display, on the monitor or printer, of the total counts per integration. This not only eliminates the need for readouts on the counter, but it enables the simultaneous display of many consecutive integrations.

(2) Graphic plots of counts on the screen or a printer.

(3) Chart recorder output (requiring digital-to-analog conversion of the binary count word, appropriately scaled in software).

Figure 7 illustrates two of these displays: (1) the chart recorder provides a hard-copy record of the data as well as notes written by the observer, and (2) a real-time video display (scrolling vertically) of the data being gathered. Also shown is the photon counter box itself, including high-voltage power supply. (Note: Many of the controls shown on this box are not needed for the simpler design described here.)

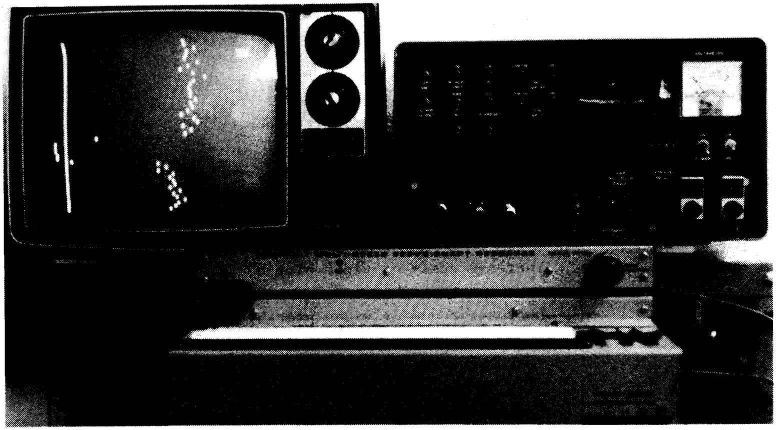


Fig. 7. Close-up of three of the elements in Figure 5. The photon counter is housed in the black box. Many of the controls and functions shown were developed prior to using the system with a computer and are no longer necessary. The computer video monitoris displaying stored count data (scrolling vertically) while the chart recorder is used to supply a real-time data map and to record notes.

Since each display output is software controlled, the plot scale can be varied in real-time to give the best possible view of the data being acquired. After each new data point is stored and displayed, the processor returns from the interrupt routine, ready for the next interrupt or a keyboard command.

III. COUNTER/TIMER

The detailed design of the counter/timer is described in this section. Figure 8 illustrates the timing involved (note that the time axis is not drawn to scale), Figure 9

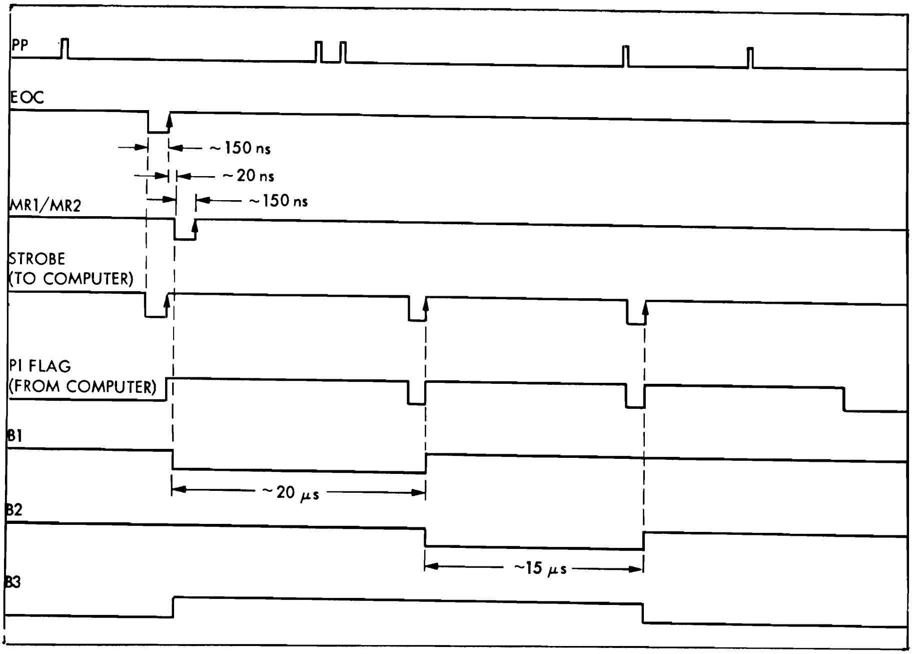


Fig. 8. Timing diagram for the counter/timer and computer interface. The time axis is not drawn to scale.

is the counter circuit, and Figure 10 is the timer schematic. Photon pulses (PP) arrive at random intervals depending on the star intensity and subject to the deadtime constraints of the amplifier/discriminator. Two related points need to be kept in mind when designing a circuit to count these pulses:

(1) Although the average count rate may be low, the counter must be capable of counting short pulses (Figure 3) separated by the minimum possible spacing that can occur (limited by the deadtime).

(2) The minimum possible pulse spacing is usually not equal to the deadtime measured using standard rolloff techniques (Rotondi *et al* 1979). This is due to the fact that the preamplifier recovery time is related to the size of the input photomultiplier pulse. Thus, a small input pulse will permit the next pulse to occur after an interval that is substantially less than the average separation. For my system, the minimum pulse separation of 40 ns (40×10^{-9}s) was measured, while the average deadtime is 68 ns.

In order not to lose counts, a counter bandwidth of at least 25 MHz (reciprocal of 40 ns) is required. This requirement is more than satisfied by using a Schottky (S) TTL counter for the first stage, and low-power Schottky (LS) counters for the remaining stages.

Photon Counting Circuit

Photon pulses are counted by a series of six 161 binary counters (Figure 9). Each 161 counts pulses from 0 to 15 (0000 to 1111 binary) with the total count (binary) available at the outputs Q_0 through Q_3 (pins 14 through 11, respectively). Since each counter has a four bit range, the six counter cascade can count up to $16^6 - 1 = 2^{24} - 1 = 16{,}777{,}215$. Although it is possible to overflow this count by integration of several seconds on a bright star, in practice this is a more than ample count range.

The first stage of this counter (C1) is a Schottky version of the 161 as explained above. Note that the incoming pulses arrive via a terminated transmission line from the telescope (50 Ω coaxial cable shown). Care should be taken to route this cable directly to the 74S161 with a minumum of unshielded wire. Under no circumstances should it be routed through the computer bus! I ran a miniature 50Ω coaxial cable to the board from a BNC connector on the counter chassis. The 25-foot cable coming from the amplifier/discriminator (telescope) is attached to the other side of this connector, on the outside of the counter/timer box. Note also that the +5V power supply is decoupled using a 0.01 μF capacitor (pin 16 of C1). A decoupling capacitor to ground should be inserted near approximately every other counter to keep the +5V supply free of glitches. Not shown on either schematic are the power and ground connections for any of the IC's: V_{cc} (+5V) is always the highest number pin (pin 16 for 161's), and GND is always the highest number pin divided by two (pin 8 for 161's).

Counter C1 is the only device which requires a very high frequency response since the rate of carry pulses (pin 15) is 1/16 that of the incoming photon pulse rate. Therefore, the output carry pulse can be stretched using a "one-shot" (OS-1) and the remaining counters (C2 through C6) hooked up as a single 20-bit synchronous counter. The 74LS221 is

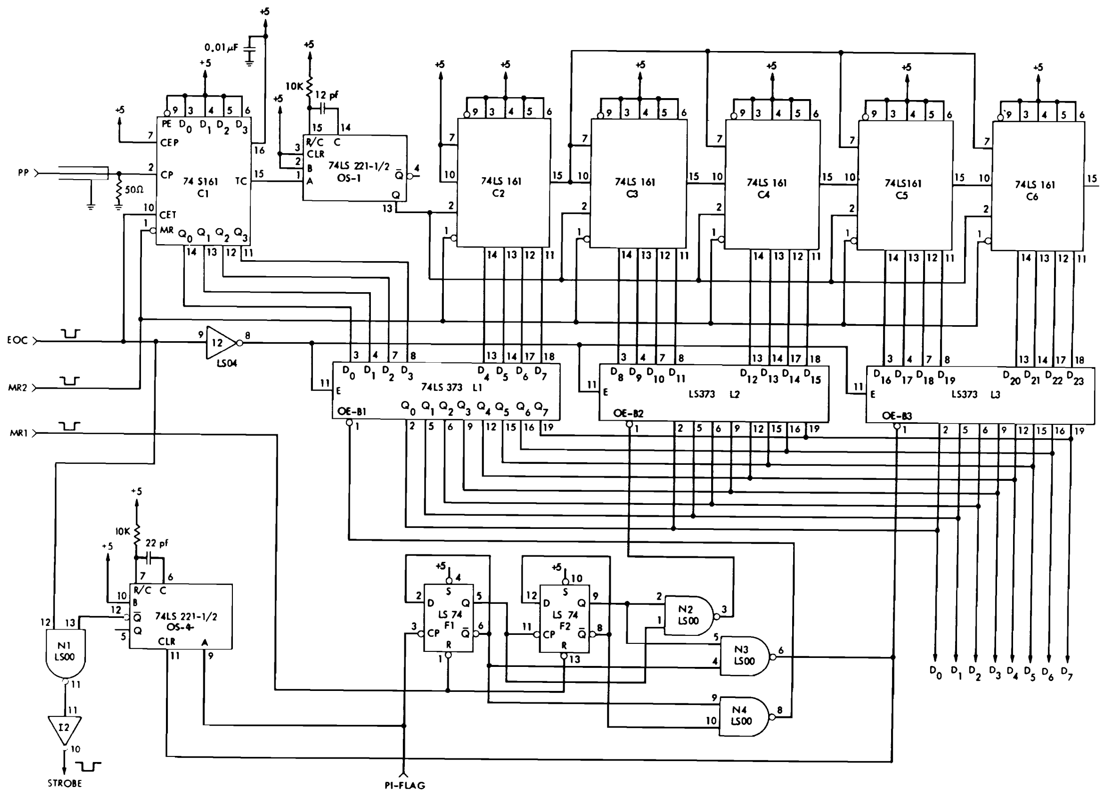


Fig. 9. Counter circuit schematic.

actually two one-shots in a single package. The other one-shot (OS-4) is used to provide two of the three data ready strobes to the computer. The pulse length for each one-shot is determined by the external resistor and capacitors shown on Figure 9. Other similar values may be substituted as long as the product RxC remains approximately constant.

The End-of Count (EOC) pulse, generated by the timer circuit (Figure 10): (1) stops the count function by driving pin 10 of C1 low (see Figure 9), (2) loads the final count into the output latches L1, L2, and L3, and (3) interrupts the computer. The Master Reset (MR) then resets all counters and the flip-flops F1 and F2. Two identical MR pulses are provided (MR-1, MR-2) in order to drive all of the required inputs. After MR returns to its normal (high) state, counting resumes for both the timer and counter chains: a new integration cycle is initiated.

The bottom waveforms of Figure 8 illustrate the timing of the counter/microprocessor data transfer. Since the microprocessor can handle only 8-bits (one byte) of data at a time, the 24-bit count word is broken into three separate reads. The two flip-flops (74LS74) and three NAND gates (74LS00) in Figure 9 generate the enable signals B1, B2, and B3 to control which byte is placed on the output data lines (D_o - D_7). The 8-bit registers (74LS373) not only latch the count data from the counters (75LS161), but also can be tied directly together to the output data lines since they have tri-state outputs (i.e. when not selected they effectively disappear from the circuit).

The sequence of events after the computer is interrupted is as follows (recall that all of these functions are being accomplished while the counters C1 through C6 are counting photons in the next integration cycle):

(1). The first STROBE pulse sent to the computer is derived directly from EOC through the NAND gate N1. This STROBE pulse not only interrupts the computer (causing it to branch to the interrupt processing routine - Table 3), but also causes the computer hardware to automatically set PI-FLAG high. Since further interrupts are ignored by the processor (until an interrupt enable is executed), additional STROBE signals can be used for handshake communication between the counter/timer and computer.

(2). Since B1 is low, the first byte of data (the eight least significant bits) is available on the output lines (D_o-D_7). This byte is input and loaded into memory and PI-FLAG is reset by software, indicating that the computer is ready to receive the next data byte.

(3). By resetting PI-FLAG, the computer causes two actions within the counter/timer. First, OS-4 is triggered to produce a second STROBE pulse. Second, Flip-Flop F1 is toggled to drive B1 high and B2 low, placing the second byte of data on lines D_o - D_7.

(4). After the second byte of data is transferred to memory, the entire process is repeated a third time. Note that when PI-FLAG is reset for the third and final time, no strobe pulse is generated by OS-4. This enables PI-FLAG to remain low, ready for the next cycle to be initiated after the integration time has elapsed.

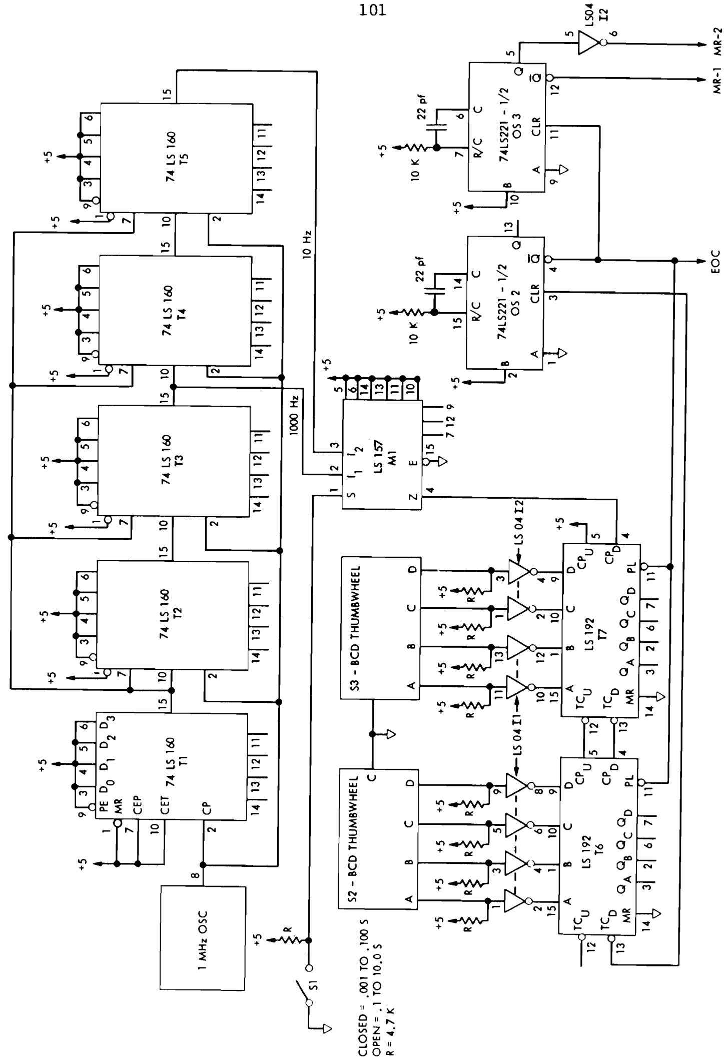


Fig 10. Timer circuit schematic.

(5). Before returning from the interrupt, the processor checks for real-time display flags, sending the new data to the monitor, chart recorder, etc., if these flags are set. Finally, interrupts are enabled and control returned to program being executed before the interrupt occurred.

Although other 8-bit computers may not have handshake signals which are identical to those shown, most 8-bit parallel ports should be able to provide the key PI-FLAG function in Figure 8. Once this is done, and an appropriate interrupt response provided, the readout of count data can be structured exactly as described. Section IV lists are assembly-level interrupt response program to handle the computer side of this interface. Appropriate software changes are, of course, required for other microprocessors.

It should also be mentioned that the same data transfer can be achieved with a polling, rather than an interrupt-driven approach. In that case, the I/O port is continually polled to see if a new data word is available. Once the new word appears, the transfer proceeds as before, after which polling is resumed. While this method does not allow the computer to perform other functions while waiting for data, it can be readily implemented in computers that do not support interrupts.

Timer

A second major logic element is the timer circuit which generates the EOC and MR waveforms. The basic circuit (figure 10) is similar to the digital telescope drive design of West and Bradford (1975). The integration interval (T_o) is controlled by two BCD thumbwheels (S2 and S3) and one range switch (S1). The thumbwheels can be set for any value between 00 and 99,and this value is loaded into the interval timer chips (T6 and T7). These counters are wired so that the actual count per interval is one larger than that displayed on the thumbwheels to enable a maximum interval of 10.0 and not 9.9 seconds.

In order to translate the preset numbers into precisely determined time intervals, counters T6 and T7 must be driven by a precisely determined clock frequency. I use a standard TTL oscillator accurate to 25 parts per million for convenience and timing accuracy. Five BCD counters (T1 - T5 in Figure 10) generate 1 KHz and 10 Hz waveforms for inputting into T7. The 74LS160's are essentially identical to the 74LS161's used for the photon counter circuit, except that they count to 9 instead of 15. Note that for the timer application, the output used is the borrow pulse (pin 15), not the output data (pins 11 - 14) as was the case in Figure 9.

The multiplexer (M1 in Figure 10) channels either the 1 KHz or 10 Hz waveforms to the interval timer chips (74LS192). These count down from the value loaded by the thumbwheel switches to -1, at which time a carry pulse on pin 13 of T6 signals that the count integration interval is over. This carry pulse triggers a one-shot (OS-2) which generates the EOC pulse and in turn triggers a second one-shot (OS-3) to generate MR-1 and MR-2. The EOC pulse is used to reload the thumbwheel readings into T6 and T7 so that the next integration proceeds without the loss of a single clock pulse.

Two points should be emphasized with regard to the timer deaign. First, Switch 1 enables the entire range of integrations between 1 millisecond and 10 seconds to be covered with only two thumbwheels (0.001 to 0.1s when 1 KHz is selected, 0.1 to 10.0s when 10 Hz is used). This range has proven to be more than adequate for all astronomical phenomena I have observed. Secondly, since the timer loses none of the pulses coming from the 1 MHz oscillator, it provides an excellent timebase for event timing. For example, as occultation observed to occur at a computer memory location 9,429 bytes into the data storage area, is known to have occurred (9,429/3) x 0.005 = 15.715 seconds after data taking was initiated (assuming a 5 ms integration).

Building Tips

Although the circuits in Figures 9 and 10 may appear forbidding, they are in reality quite easy to build. If carefully wired, there is no reason why successful operation cannot be achieved on the first application of power. However, if problems occur, a logic probe for testing which points are oscillating, which are at +5V, and which are at ground can be invaluable. An oscilloscope is of course the ideal tool for debugging simple logic, if one is available.

The following comments address several of the questions concerning the fabrication of these circuits:

(1). Physical Configuration: The circuits in Figures 8 and 9 can be located in a box separate from the computer or they can be in a computer prototyping board within the computer itself. I adopted the former approach for historical reasons (the computer came three years after the counter/timer). If a separate box is chosen, it should be possible to borrow enough raw power (8V to 20V) from the computer to avoid having to build a complete 110V power supply from scratch. Each board then contains a 5V regulator circuit (Figure 11) to provide V_{cc} to all circuits. The interface with the computer is made via a parallel input port with the appropriate handshake signals (STROBE, PI-FLAG) described previously.

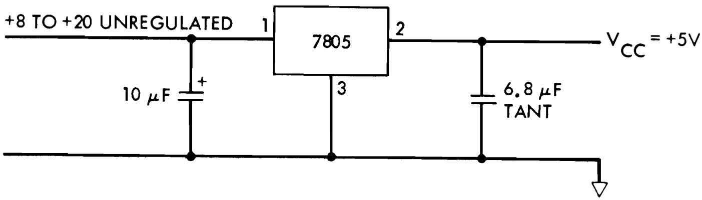


Fig. 11. Voltage regulator schematic.

The alternate approach, a prototype board which fits into the computer card cage and has direct access to the computer bus, has a number of advantages:

(a) There is no need for a separate box.
(b) Power is readily available.
(c) The computer addresses and data busses can be directly accessed.

The big disadvantage of this alternative is that additional circuitry to decode addresses and process the interrupt must be provided in the counter/timer design. For this reason, use of a separate box and parallel input port has been assumed.

(2) Boards and Card Cage: A number of different boards and card cages are available. I prefer boards designed for soldering which have interlaced power and ground metalization strips (Figure 12). Wire wrap is an alternate technique finding increasing acceptance. Probably the best approach to selecting a configuration is to visit a local computer products distributor or send for catalogs. (Many computer stores are disappointing for "nuts and bolts" purchases - they often sell only turn-key systems and software.)

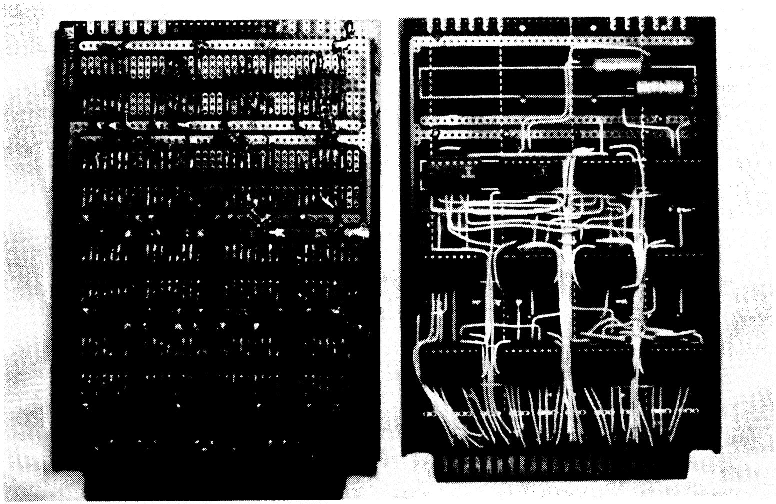


Fig. 12. Typical solder circuit boards - note that IC'c are all in sockets.

(3) Fabrication Techniques: All IC's should be mounted in sockets for ease of replacement. Before the integrated circuits are installed, each socket should be tested to verify that V_{cc} and GND pins are at the correct potential when the power is on. Once these pin voltages are checked, the IC's may be inserted and power reapplied.

(4) Bill of Materials: Typical prices, taken from the current magazines and suppliers catalogs, are listed in Table 2. It is advisable to buy at least one spare of each IC in the event of a failure in the field. With simple diagnostic tools such as a logic probe, one can usually pinpoint a failed chip in an operating circuit. After a few initial burn-in failures (infant mortality), my equipment has operated for the last five years without failure.

TABLE 2: COUNTER/TIMER BILL OF MATERIALS

Quantity	Item	Total Cost ($)
1	Prototyping Boards 9.6 x 4.5 inches	12.00
1	Edge Connector	2.50
25	Dip sockets @ $.20 each	5.00
24	Integrated circuits as follows;	
	1 74LS00 @ $.24	.24
	2 74LS04 @ .24	.48
	1 74LS74 @ .35	.35
	1 74LS157 @ .65	.65
	5 74LS160 @ .69	3.45
	5 74LS161 @ .65	3.25
	1 74S161 @ 1.95	1.95
	2 74LS192 @ .79	1.58
	2 74LS221 @ .89	1.78
	3 74LS373 @ .99	2.97
	1 LM7805K @ 1.29	1.29
		17.99
1	TTL Oscillator	30.00 (approx.)
1	BCD Thumbwheel Switches (2-digit)	15.00 (approx.)
	Miscellaneous (resistors, capacitors, etc.)	5.00
	TOTAL (Counter/Timer)	$88.00

TABLE 2 (Continued)

SUPPLIERS

1. Boards, connectors, IC's, sockets: See advertisers in BYTE magazine.

2. TTL Oscillator	a.	Vectron Laboratories 166 Glover Avenue Norwalk, CT 06850
	b.	Conner-Winfield Corporation West Chicago, IL 60185 Phone: (312) 213-5270
	c.	Motorola Components Products Dept. 2553 N. Edgington Franklin Park, IL 60131
3. BCD Thumbwheels	a.	Gateway Electronics 8123-25 Page Blvd. St. Louis, MO 63130
	b.	Local Distributors

IV. SOFTWARE

This section briefly describes examples of two types of software programs required for this system. Table 3 is an assembly language program which responds to the interrupt generated by the Counter/Timer circuit by recording and storing the 24-bit data. The second program, Table 4, is a very simple BASIC subroutine to translate 24-bit binary data into a BASIC floating point variable for use in other BASIC programs.

These programs, which are written in Z-80 assembly language and North Star BASIC, respectively, are intended as examples to those comtemplating a similar system. It is not expected that they could be used directly since every user will have different requirements. Once count data has been stored in memory, the processing options available are limited only by the skill and imagination of the programmer.

Data Input Subroutine

Assembly language programming has an aura which is quite undeserved. Contrary to popular belief, basic assembly techniques can be easily mastered, and successful interface programs written after a few hours of study. A good place to start is an assembly language programming manual for the microprocessor/computer to be used. It should contain a table summary of the complete instruction set so that questions regarding the availability and use of particular instructions can be readily answered. Initial programs can be assembled by hand, thereby avoiding the need to become proficient in both the language and the assembler simultaneously.

The program in Table 3 is entered automatically after the interrupt from the counter/timer is received, and it performs the following functions:

(1) Save the contents of registers to avoid upsetting the interrupted program.

(2) Read three bytes of data and store in the memory.

(3) Increment the data pointer so that the next 24-bit data word will be stored in the next three bytes of memory.

(4) Check for various display options (monitor, chart recorder, printer) and call appropriate software routine if flags are set.

(5) Check for end of storage memory - if end is reached, either stop or recycle, depending on the recycle flag. (The ability to recycle memory can by useful for events such as occultations, where at 0.001s per sample, the memory will fill up in a few seconds.)

(6) Restore saved registers (POP register data from Stack).

(7) Enable interrupts (further interrupts were automatically disable by the interrupt which caused the branch to this program).

(8) Return to the interrupted program.

Comments in Table 3 show how these functions are performed in the Z-80 microprocessor (with North Star I/O port assignments). The first column of the Table also lists the computer memory addresses where the program is located (in hexadecimal). The program occupies only 5C(hex) = 92 bytes of memory. If no display options are exercised, the entire program is executed in 87 microseconds (with a 4 MHz clock), in plenty of time for the next count word even at 1 ms per sample. With fast display options, such as a chart recorder, a one millisecond integration can still be supported. However, slower processes, such as a video plot or a printer output cannot be operated in real-time at the very highest rates.

TABLE 3: PROGRAM

Address	Assembled Code	Mnemonic	Comment
0100	F5	Push AF	Save register pairs
0101	E5	Push HL	
0102	C5	Push BC	
0103	2ACB03	LD HL, [03CB] :	Load HL with data pointer
0106	DB00	IN A,00 :	Input first byte (LSBs)
0108	77	LD[HL],A :	Store byte in memory
0109	3E30	LDA,30	Reset PI-FLAG
010B	D306	OUT06,A	
010D	23	INC HL :	Increment data pointer
010E	DB00	IN A,00	Repeat for second byte
0110	77	LD[HL],A	
0111	3E30	LDA,30	
0113	D306	OUT06,A	
0115	23	INC HL	
0116	DB00	IN A, 00	Repeat for third byte
0118	77	LD[HL],A	
0119	3E30	LD A, 30	
011B	D306	OUT06,A	
011D	23	INC HL	
011E	22CB03	LD[03E1],HL :	Load new pointer into memory
0121	2AE103	LD A [03E1]	Call video subroutine if flag = 01
0124	FE01	CP 01	
0126	CC0002	Call on zero	
0129	2AE203	LDA, [03E2]	Call CR subroutine if flag = 01
012C	FE01	CP 01	
012E	CC0003	Call on zero	
0131	2AE303	LDA[03E3]	Call printer if flag = 01
0134	FE01	CP 01	
0136	CC0004	Call on zero	
0139	7C	LDA,H	Check if memory full - if not jump to 0157
013A	FEC0	CP C0	
013C	2019	JR NZ, 19	
013E	2AE403	LDA,[03E4]	Check recycle memory flag, jump if 01
0141	FE01	CP01	
0143	280C	JR Z, 0C	
0145	3E21	LDA, 21	If don't recycle memory, signal with "!!" and Return, without enabling interrupts
0147	CD0029	Call COUT	
014A	CD0029	CALL COUT	
014D	C1	POP BL	
014E	E1	POP HL	
014F	F1	POP AF	
0150	C9	RET	
0151	21002A	LD HL, 2A00	If recycle memory, load data pointer with 2A00
0154	22CB03	LD[03CB],HL	
0157	C1	POP BC	Restore registers
0158	E1	POP HL	
0159	F1	POP AF	
015A	FB	E1 :	Enable interrupts
015B	C9	RET :	Return

TABLE 3 (Continued): DATA INPUT INTERRUPT SUBROUTINE

PARAMETER STORAGE

Location	Contents
03CB, C	Pointer to next unused location in data table
03E1	Video display Flag = 01 for real-time display
03E2	Chart Recorder Display Flag = 01 for real-time CR plots
03E3	Printer Flag = 01 for real-time decimal printout
03E4	Recycle Flag = 01 for recycle memory if full

Starting storage memory address = 2A00

Final storage memory address = BFFF

TABLE 4: BASIC ROUTINE TO READ A PHOTON COUNT WORD

CALLING PARAMETER:
X = Address of desired 24-bit count word
OUTPUT:
Y = Total counts in BASIC (Floating point) format

```
10 A1 = EXAM(X)
20 A2 = EXAM(X+1)
30 A3 = EXAM(X+2)
40 Y  = A1 + 256*A2 + 65536*A3
50 RETURN
```

Basic Routine

Table 4 contains an extremely simple routine to read the binary photon count data and convert it into a BASIC floating point number (Y). The key is the "EXAM" statement (also called "PEEK" in many BASIC's) which takes a single byte and converts it into a BASIC variable. Note that the data in memory is stored with the least significant byte first, as discussed in the counter/timer description.

V. OBSERVATION EXAMPLES

Several examples of observational results achieved with this system are described below. Most of the results were obtained using the author's 16-inch Cassegrain telescope located on a site near Joshua Tree, California. This location (high desert) is in many ways ideal for photometry. The sky background is not only quite low ($m_V \sim 21$ per square arcsec), but it is also usually very constant throughout the night. Small variations in sky transparancy, which play havoc with photometric accuracy, are also rare. On the negative side, the seeing is often on the order of 5 arcsec, which, while a drawback to visual observations, does not seriously degrade most photoelectric measurements.

Comparison Star Sequences

One application which has received a major fraction of my observing time has been the measurement of comparison star sequences for the AAVSO variable star fields. Early in this work it became evident that sequence errors, that is inaccuracies in the magnitudes assigned to comparison stars, are perhaps the largest source of error in the final measured light curve (Stanton 1981a).

Sequence errors degrade visual observation by contributing both *systematic* distortions and *random* noise (observation scatter) to the final light curve. Errors of 0.5 to 1.0 stellar magnitudes, or more, are not uncommon in sequences measured by non-photoelectric means. Therefore, the use of photoelectrically measured comparison star sequences should result in significantly improved accuracy for visual light curves.

The color response for the dark adapted eye differs considerably from that of the photoelectric V bandpass (Stanton 1981a). Therefore, a correction must be applied to translate V into m_V (visual magnitude) which depends on star color (B-V). An empirical relationship for this correction as derived in the above reference is:

$$m_V = V + 0.182\ (B-V) - 0.15\ . \qquad (1)$$

Table 5 lists the requirements for a photoelectrically measured sequence. Although it might be argued that somewhat less accuracy is acceptable, the reduction of errors to better than $\pm\ 0\overset{m}{.}02$ should be achieved for all photometry (except for the faintest stars). A photon counting system is ideal for this work since stars can be readily observed over a wide range of magnitudes, down to the faintest stars visible. Both the quantum-limited performance at low light levels, and the extreme linearity (after correction for deadtime) over many magnitudes, are important system attributes for achieving this range.

A typical observing run proceeds as follows:

(1). The integration time is set for 2.0 seconds, the diaphram at 22 arcsec, and the computer is initialized. From this point on, count samples are automatically collected and stored in the computer without further intervention. A two-second integration gives plenty of time resolution, and over 5 hours of continuous data storage.

Table 5

Photoelectric Sequence Requirements

PARAMETER	VALUE	COMMENTS
Colors	B, V	Need V and B-V in order to calculate visual magnitude
Accuracy	±.02 mag (bright) ±.05 mag (faint)	Extreme accuracy is not required; however, should pay close attention to systematic errors.
Brightness	$m_V = 6$ to 16	Sequence should range from approximately one magnitude brighter than variable maximum to one magnitude fainter than minimum (if possible).
Brightness Separation		Gaps between consecutive comparison stars should be less than 0.5 magnitude if stars are available.
Star Color	$0.3 < B\text{-}V < 1.5$	Color extremes; particularly very red stars, should be avoided.
Angular Separation		As small as possible from variable, preferably located at a variety of position angles.

(2). At least two standard stars are observed (B,V) within 10 to 15 degrees of the variable. During the course of the next few hours, these stars are occasionally observed up to an air mass at least 2.0 in order to determine the extinction coefficients. (If a new field is observed, coefficients from previous standard stars can be transferred). Care should be exercised in selecting standard stars since many published magnitudes have substantial errors. When no suitable standards are available from standard lists (Johnson 1963), stars having three or more consistent measurements in the U.S. Naval Observatory Photoelectric Catalog (Blanco *et al* 1974) are used.

(3). Background readings are made at three or more times during the measurement of sequence stars, with emphasis given to times when faint comparison stars are observed. One key to accurate photometry of very faint stars is to find a background region where no stars exist within 2-3 magnitudes beyond the telescope limit. This requires either a very good star map or, more commonly, examination of a photograph of the field in question. If this precaution is not taken, invisible stars can distort background measurements and may lead to substantial magnitude errors for the faintest stars. (For example, if the background were measured with a 17th magnitude star in the diaphram in table 7, the additional 2.5 counts per second added to the V background would increase the measured magnitude of star #5 from 15.61 to 15.96.)

(4). Sequence stars are centered in the diaphram and measured (B and V) for periods between 20 and 200 seconds, depending upon the brightness. During each observation the measured counts (each 2 seconds) are plotted on both video monitor and chart recorder. Notes are written on the chart recorder paper to assure that an adequate data log is kept. The video plot is continuously monitored so that anomalies, such as clouds or pointing drifts, can be immediately detected.

Processing of the sequence data is accomplished off-line, usually several days after the observation. The addresses for each measurement are determined using the video plot routine. If part of a measurement is defective (i.e. wind caused the image to partially leave the diaphram) only that portion giving a consistently level trace is selected. These addresses are then input into a BASIC program (Table 6) which calculates fully corrected V and B-V (Table 7) for each star.

The details of the comparison star program are provided in annotations on the listing in Table 7. Very briefly, the program performs the following calculations:

(1). A raw count value is calculated for each measurement (background, standard, sequence star) based upon input data address locations (a scale factor, which was required on an earlier system due to prescaling for very bright stars, is not required with the 24-bit system described here). This is equivalent to, but much more accurate than, measuring the deflection of a chart recorder trace.

(2). All readings are corrected for deadtime and interpolated background readings subtracted from all star measurements.

(3). Standard star readings are used to calculate standard reference and extinction coefficients.

(4). V and B-V values are derived using standard formulae (Hardie 1962), and m_v calculated using equation 1.

(5). Finally, all data are printed out to provide a permanent and detailed record of the observations (see Table 7).

On a good night with adequate preparation (standard stars and background areas selected), four to five complete sequences of approximately 15 stars each can be measured. Observing time is fully occupied in pointing the telescope, checking to see that good count data are being recorded, and writing down pertinent parameters such as the star and filter ID, etc.

Experience has shown that it is extremely useful to measure known sequences, such as those measured by the U.S. Naval Observatory (Priser 1974), to provide an overall check of the system performance. This should be done from time-to-time, even after the system is fully calibrated. Since these sequences typically run over seven or more stellar magnitudes, they provide an acid test for how well the system is really working.

Recording of Transient Events

A completely different mode of operation is required for observing events characterized by rapid changes in brightness. Here, photometric accuracy is usually not as important as achieving adequate time resolution and fast data recording. Figures 13, 14, and 15 show three types of occultations observed with this system, ranging from a very fast stellar occultation to the much slower disappearances of the Galilean satellites.

Figure 13 illustrates that data can be recorded at a rate which is too high for either a manual or a chart recorder-based system. If an integration time (T_o) is too short, the count data can be recombined later to give the appropriate balance between noise and time resolution. Furthermore, since no time constants are inherent in the system (other than the count interval inself), there is no distortion in fast events caused by filtering. If filtering is desired, it can be added after the fact.

A number of non-astronomical sources have also been observed to illustrate the system's time resolving potential: Figure 16 shows a typical street light signature, which is nearly 100% modulated at twice the line frequency (i.e. 120 Hz). Figure 17 illustrates the more complex light variation of the computer video monitor. These and other waveforms have been examined in the frequency domain using FFT techniques, with fascinating results (Figure 18).

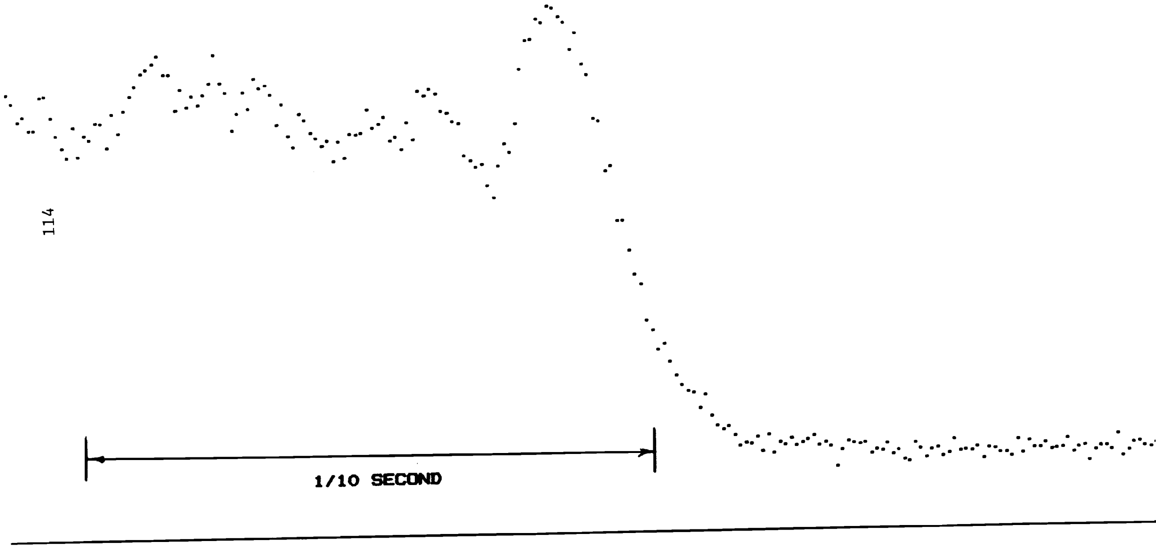


Fig. 13. Lunar occultation of 75 Tau (m_V=5.3) on March 4-5, 1979 showing typical interference pattern. Integration = 0.001 seconds.

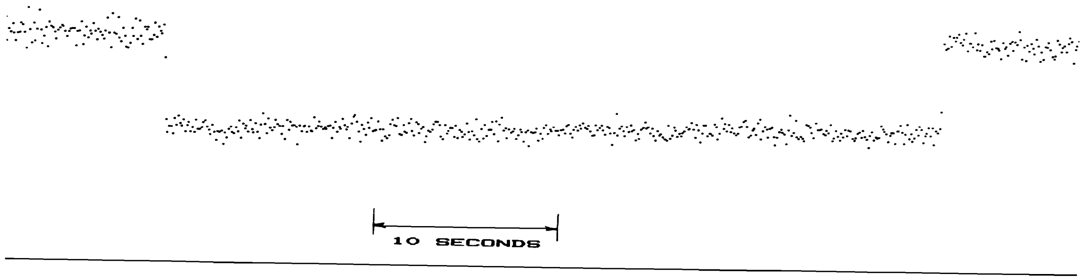


Fig. 14. Occultation of a $9^{m}.8$ star by Juno on December 10-11, 1979. Integration = 0.1 seconds.

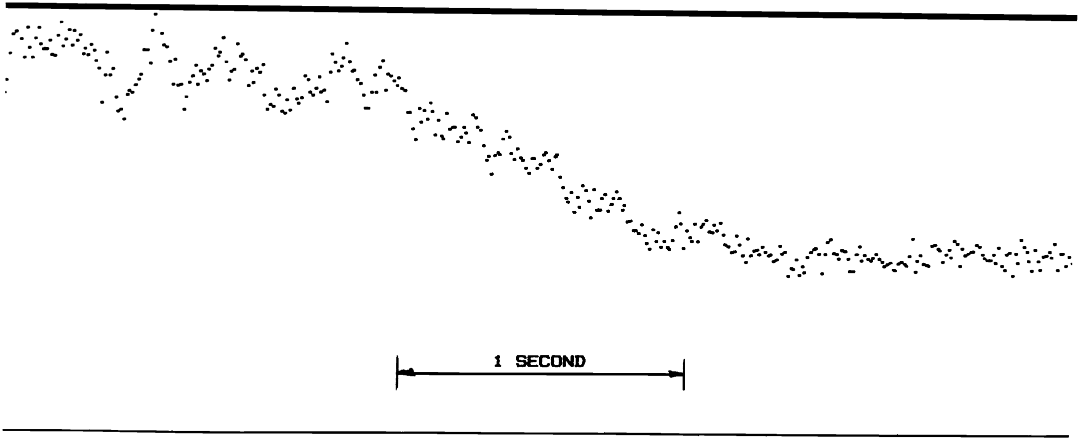


Fig. 15. Occultation of Io on July 16-17, 1980. Integration = 0.01 seconds.

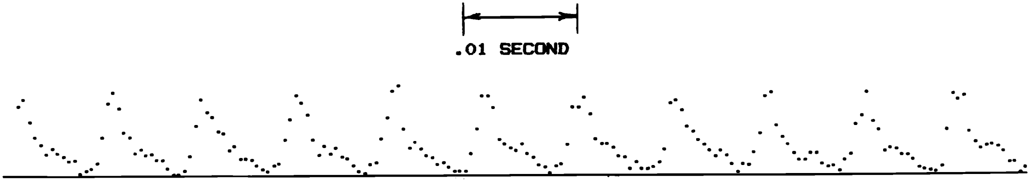


Fig. 16. Mercury vapor street light (integration = 0.0005 seconds. Note that the light is essentially 100% modulated at 120 Hz.

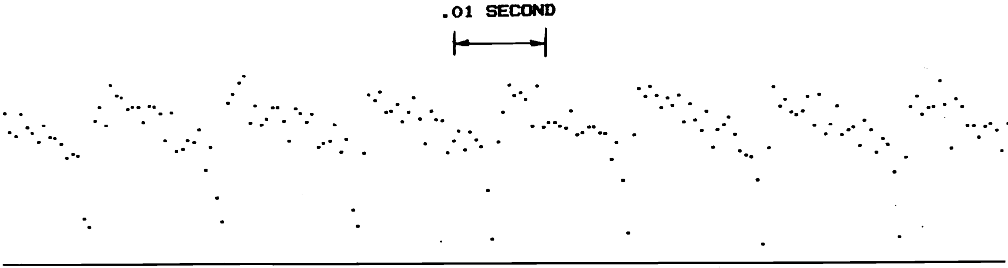


Fig. 17. Time variation of the computer monitor (TV screen) light intensity. Integration = 0.0006 seconds. Note that the 60 Hz frame rate is evident.

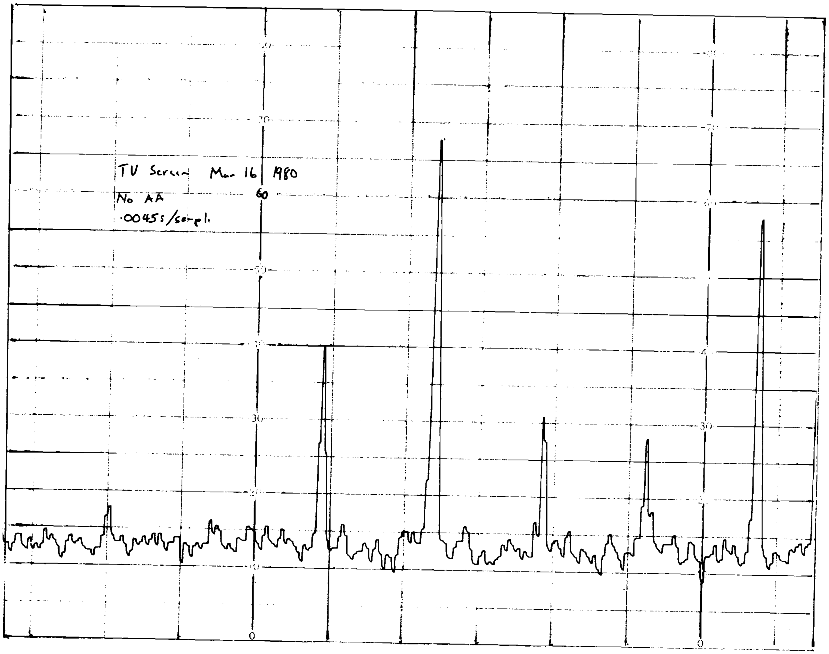


Fig 18. Fast Fourier Transform (FFT) spectrum of the TV monitor from data similar to that shown in Figure 17. Spectrum covers frequencies from 0 to 111 HZ. Frequencies higher than the fundamental (60 Hz) are due to information content in the TV picture.

Variable Stars

Finally, the application of the system to variable star observation provides a seemingly endless renge of possibilities. Figures 19 through 22 illustrate some of the typical results for stars varying on the timescale of minutes.

Another possibility which I have not as yet pursued is the automatic monitoring of flare stars. The computer could be programmed to continually look at the incoming data to see if a significant increase (say 5%) in star brightness had occurred. Once an increase was detected, an alarm could be sounded summoning the observer back to the telescope. As long as no flare was detected, the memory could be continuously recycled each time the data area filled up (e.g. every 30 minutes at 0.1s per sample).

VI. SUMMARY

A computer-based photometric system has been described which can support a wide range of astronomical investigations. The following performance characteristics have been achieved with this design:

(1). Magnitude range: 12 magnitudes or more
(2). Limiting magnitude: Faintest star visible (or fainter if the star can be found)
(3). Integration range: 0.001 to 10 seconds
(4). Count range: 0 to 16,777,215 per integration
(5). Dark count: Less than 8 counts per second at room temperature
(6). Photometric accuracy: Limited only by calibration and counting statistics

It is my opinion that despite the electronic complexities involved, the most challenging elements of this system were the design and fabrication of the optical head, and the improvement of the telescope clock drive to eliminate tracking errors. The system's performance has more than compensated for the additional effort required for implementing photon counting and the computer interface

VII. ACKNOWLEDGEMENT

The author is indebted to Howard Primas of the Jet Propulsion Laboratory for his extensive help in the early phases of the counter/timer development.

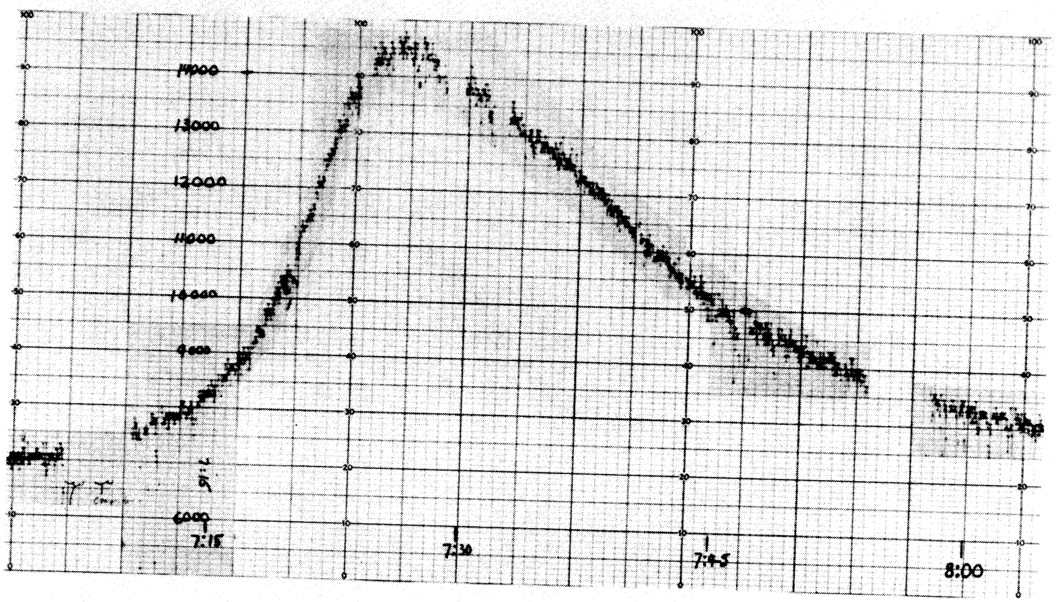


Fig. 19. Most of one cycle of the short period RR Lyrae star, CY Aquarii. This star is sufficiently bright ($10^{m}.6$ - $11^{m}.5$) that the moon light on this night had only a minor effect. (B filter/2s integration).

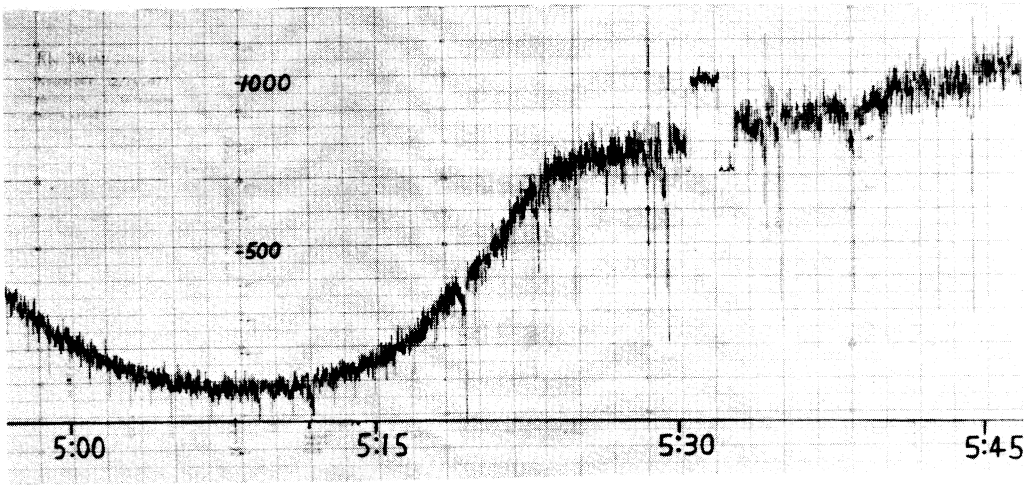


Fig. 20. Eclipse of RW Triaguli ($13^{m}.5$ - $16^{m}.0$) on November 12-13, 1977, showing the short duration eclipse (30 minutes) and a suggestion of flickering agter the recovery to maximum. The numerous dropouts in the trace after maximum show the effect of a poorly performing clock drive (which has since been replaced).

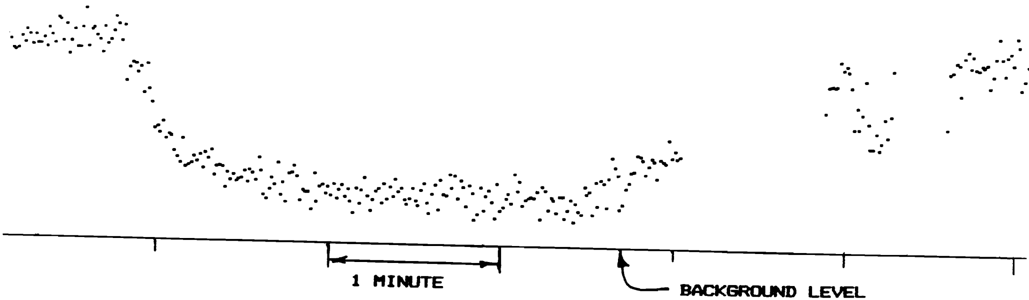


Fig. 21. An eclipse of HT Cas measured on August 3-4, 1981 using the historic 60-inch telescope on Mt. Wilson. Since the star was not having an outburst at the time, its magnitude faded from approximately 16 to 18 during the 5-minute eclipse. Integration = 2 seconds.

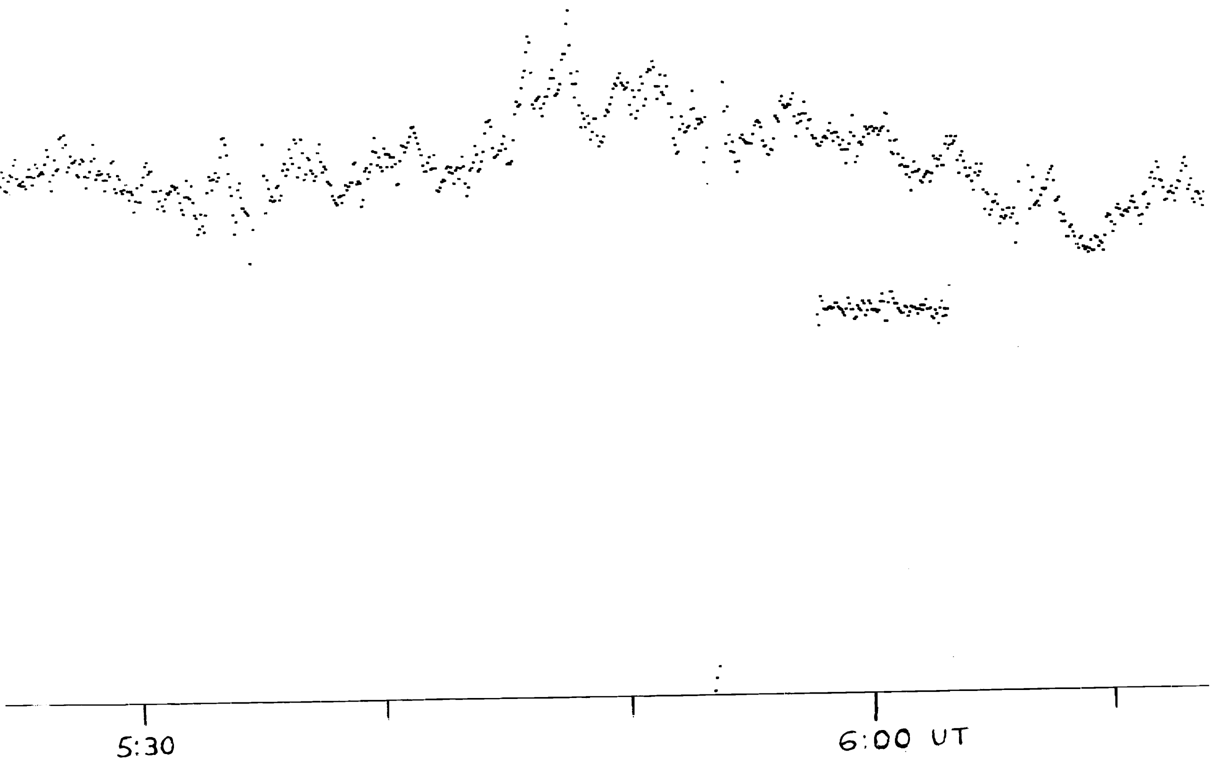


Figure 22. Brightness variations of AM Her ($13^{m}.0$) on the night of June 13/14, 1983 (Universal Time given for June 14). With no filter and a 4-second integration, a peak count of approximately 6400 counts/sample was measured. The many oscillations in the light curve are typical for AM Her in its active state (caused by X-rays from a neutron star striking its companion). That the oscillations are real, and not due to instrumental effects or tracking errore, is demonstrated by the short measurement of a nearby star ($13^{m}.1$, shown below AM Her curve) which exhibits only noise effects.

TABLE 6

STAR MAGNITUDE REDUCTION PROGRAM

This program calculates V and B-V magnitudes based on photon count data (stored in 16-bit binary form) and address and other information loaded by the operator. The first step is to load the S(I,J) matrix with data as follows:

I=0	Tells computer to skip data input
I=1-15	Star # (maximum number of stars is 15)
I=17-26	Background data (maximum number of background points=10)
I=28-32	Standard star measurements

NOTE: I=1 should be used for the second standard (checkstar) if available

J=0	V start address
J=1	V finish address
J=2	B start address
J=3	B finish address
J=4	Normalization factor
J=5	(not used)

```
24 DIM A$(4),S(32,5),Z(4)
25 INPUT "FILE NAME ",C$
30 GOSUB 2000
40 INPUT "STAR NO. ",J
45 IF J=0 THEN 125
50 IF J>15 THEN 65
55 GOSUB 2100
60 GOTO 40
65 INPUT "BACKGROUND POINT NO.  ",J
70 IF J=0 THEN 125
75 IF J>10 THEN 95
80 J=J+16
85 GOSUB 2100
90 GOTO 65
95 INPUT "STANDARD POINT NO.  ",J
100 IF J=0 THEN 125
105 IF J>5 THEN 125
110 J=J+27
115 GOSUB 2100
120 GOTO 95
```

Now all addresses are loaded in the S matrix. Before proceeding with the computation, load input data on disk and display for check.

```
125 GOSUB 2200
130 INPUT "DISPLAY ADDRESSES?  ",B$
135 IF B$<>"Y" THEN 185
145 J=1\GOSUB 2300
150 INPUT "DISPLAY BACKGROUND/STD?  ",B$
155 IF B$<>"Y" THEN 175
160 J=17\GOSUB 2300
170 J=28\GOSUB 2300
175 INPUT "CHANGE VALUES?  ",B$
176 IF B$="Y" THEN 40
```

Before calculating magnitudes, the address matrix is converted into a data matrix by computing average count value (corrected for deadtime and with background subtracted), average V address, and the total spread (DV or DB) for each measurement. S(I,J) values are redefined as follows:

J=0	Average address (V)	J=4	DV= (Peak-Low)/Average for V
J=1	Average V (counts/s)	J=5	DB= (Peak-Low)/Average for B
J=3	Average B (counts/s)		

```
185 GOSUB 2400
190 INPUT "DISPLAY STAR COUNTS (MINUS BKD)?  ",B$
195 IF B$<>"Y" THEN 205
200 J=1\GOSUB 2500
205 INPUT "DISPLAY BKD/STD COUNTS?",B$
210 IF B$<>"Y" THEN 230
215 J=17\GOSUB 2500
220 PRINT TAB(8),"STANDARD STAR DATA"
225 J=28\GOSUB 2500
```

Input data required for calculating airmass, magnitudes, etc.

```
230 INPUT "V,B-V:  ",M1,M2
231 INPUT "JULIAN DATE--244XXXX:  ",J8
235 INPUT "STD: RA(H,M);DEC(D,M):  ",P1,P2,P3,P4
236 R1=P1\R2=P2\R3=P3\R4=P4
240 GOSUB 2600
245 T1=X\T2=Y
246 INPUT "STD#2:  ",P1,P2,P3,P4
247 S1=P1\S2=P2\S3=P3\S4=P4
248 GOSUB 2600
249 H=X\G=Y
250 INPUT "VAR:  ",P1,P2,P3,P4
251 Q1=P1\Q2=P2
255 GOSUB 2600
260 T3=X\T4=Y
265 INPUT "PST FOR START ADDR(H,M):  ",P1,P2
275 GOSUB 2650
```

Since data points are taken at exactly 2 second intervals, the starting address (line 280) establishes a timing reference for the entire data set.

```
280 INPUT "START ADDR:  ",A$
285 GOSUB 1000
290 T6=X
300 GOSUB 2700
305 GOSUB 2800
310 E=-.0414
315 F=1.0457
320 F1=F*K2\F2=F*K4
```

Before outputting star data, the program lists extinction coefficients calculated in subroutine 2800.

```
325 ! "   Kv'=",%6F3,K1,"   Kv''=",%6F3,K3,"   Kvb'=",
330 ! %6F3,K2,"  Kvb''=",%6F3,K4,"   X0=",%7F3,X0
335 ! %10F2,V0,%10F2,B0,%20F4,E,%12F4,F
```

This loop calculates, and displays on the monitor, all star magnitude data.

```
345 FOR I=1 TO 15
350 IF S(I,1)<1 THEN EXIT 416
360 GOSUB 500
405 ! %4I,I,%8F3,M,%12F3,V,%8F3,B,%12F0,S(I,1),
410 ! %8F3,S(I,3)/S(I,1),%8F3,S(I,2)
415 NEXT
416 INPUT "PRINTOUT ALL DATA? ",B$
417 IF B$<>"Y" THEN 420
418 GOSUB 3000
420 GOTO 230
```

SUBROUTINE 500---Calculates V,B and Mv including extinction and instrument corrections.

```
500 A=S(I,2)-X0
510 C=(S(I,2)+X0)/2
520 B=1.0857362*LOG(S(I,1)/S(I,3))
530 X=B-B0
540 D=F*X-F1*A-F2*C*X
550 X=-1.0857362*LOG(S(I,1))-V0
560 Y=X-K1*A+E*D-K3*A*D
570 V=M1+Y
580 B=M2+D
590 M=V+.182*B-.15
600 RETURN
```

SUBROUTINE 1000---Converts 4 digit hexadecimal addresses into BASIC integers.

```
1000 FOR N=1 TO 4
1005 Z(N)=ASC(A$(N,N))
1010 IF Z(N)>58 THEN 1025
1015 Z(N)=Z(N)-48
1020 GOTO 1030
1025 Z(N)=Z(N)-55
1030 NEXT
1035 X=4096*Z(1)+256*Z(2)+16*Z(3)+Z(4)
1040 RETURN
```

SUBROUTINE 1100---Converts BASIC integer into 4 digit hexadecimal.

```
1100 FOR N=1 TO 4
1105 M=16^(4-N)
1110 L=INT(X/M)
1115 X=X-L*M
1120 IF L>9 THEN 1135
1125 L=L+48
1130 GOTO 1140
1135 L=L+55
1140 A$(N,N)=CHR$(L)
1145 NEXT
1150 RETURN
```

SUBROUTINE 1200---Reads a block of 16-bit binary data from memory, starting with address A and finishing with address B. Finds average value and multiplies time scale factor C. Also calculates dispersion between maximum and minimum values (Z).

```
1200 Y=0
1201 M=0
1202 L=100000
1203 IF A<100 THEN RETURN
1205 N=(B-A)/2
1210 FOR D=1 TO N
1215 K1=A+(D-1)*2
1216 G=EXAM(K1)
1217 H=EXAM(K1+1)
1218 P=256*H+G
1219 Y=Y+P
1220 IF P<M THEN 1222
1221 M=P
1222 IF P>L THEN 1224
1223 L=P
1224 NEXT
1225 Z=(N*(M-L))/Y
1237 IF N=0 THEN 1250
1240 Y=Y*C/N
1242 Y=Y/(1-Y*6.7E-8)
1245 X=(A+B)/2
1250 RETURN
```

SUBROUTINE 1400---Calculates background reading for observation time specified by address A. K=0: V background, K=2: B background

```
1400 IF A>S(17,K) THEN 1410
1405 X=S(17,K+1)\RETURN
1410 FOR J=17 TO 26
1415 IF S(J,K+1)<1 THEN EXIT 1435
1420 IF A<S(J,K) THEN EXIT 1440
1425 NEXT
1430 X=S(J,K+1)\RETURN
1435 X=S(J-1,K+1)\RETURN
1440 G=(A-S(J-1,K))/(S(J,K)-S(J-1,K))
1445 X=S(J-1,K+1)+(S(J,K+1)-S(J-1,K+1))*G
1450 RETURN
```

SUBROUTINE 2000---Reads previously written address data from disk file.

```
2000 OPEN #0,C$
2005 FOR I=1 TO 5
2010 K=I+5\L=I+10\M=I+16\I+27\P=I+21
2015 READ #0,S(I,0),S(M,0),S(M,2),S(N,0),S(N,2)
2020 READ #0,S(K,0),S(P,0),S(P,2)
2025 READ #0,S(L,0)
2030 READ #0,S(I,1),S(M,1),S(M,3),S(N,1),S(N,3)
2035 READ #0,S(K,1),S(P,1),S(P,3)
2040 READ #0,S(L,1)
2045 FOR J=2 TO 3
2050 READ #0,S(I,J),W,X,Y,Z
2055 READ #0,S(K,J),W,X
2060 READ #0, S(L,J)
2061 NEXT
2065 READ #0,S(I,4),S(M,4),X,S(N,4),Y
2070 READ #0,S(K,4),S(P,4),X
2075 READ #0,S(L,4)
2076 NEXT
2080 CLOSE #0
2085 RETURN
```

SUBROUTINE 2100---Inputs address data from keyboard.

```
2100 FOR K=0 TO 3
2105 PRINT "ELEMENT NO:  ",J,K,
2110 INPUT A$
2115 GOSUB 1000
2120 S(J,K)=X\NEXT
2125 PRINT "ELEMENT NO:  ",J,"4",
2130 INPUT B
2135 S(J,4)=B
2140 RETURN
```

SUBROUTINE 2200---Writes address data onto disk file.

```
2200 OPEN #0,C$
2205 FOR I=1 TO 5
2210 K=I+5\L=I+10\M=I+16\N=I+27\P=I+21
2215 WRITE #0,S(I,0),S(M,0),S(M,2),S(N,0),S(N,2)
2220 WRITE #0,S(K,0),S(P,0),S(P,2)
2225 WRITE #0,S(L,0)
2230 WRITE #0,S(I,1),S(M,1),S(M,3),S(N,1),S(N,3)
2235 WRITE #0,S(K,1),S(P,1),S(P,3)
2240 WRITE #0,S(L,1)
2245 FOR J=2 TO 3
2250 WRITE #0,S(I,J),W,X,Y,Z
2255 WRITE #0,S(K,J),W,X
2260 WRITE #0, S(L,J)\NEXT
2265 WRITE #0,S(I,4),S(M,4),X,S(N,4),Y
2270 WRITE #0,S(K,4),S(P,4),X
2275 WRITE #0,S(L,4)\NEXT
2280 CLOSE #0
2285 RETURN
```

SUBROUTINE 2300---Displays star data addresses on video monitor.

```
2300 PRINT J,"   ",
2305 FOR I=0 TO 3
2310 X=S(J,I)
2315 GOSUB 1100
2320 PRINT A$,"   ",
2325 NEXT
2330 ! S(J,4)
2335 J=J+1
2340 IF J>32 THEN RETURN
2345 IF S(J,0)<1 THEN RETURN
2350 GOTO 2300
```

SUBROUTINE 2400---Cycles through star data table (S(I,J)) and converts memory addresses into photon counts (see comment after line 176).

```
2400 FOR I=1 TO 32
2402 A=S(I,2)
2404 B=S(I,3)
2406 C=S(I,4)
2408 GOSUB 1200
2410 S(I,2)=X
2412 S(I,3)=Y
2414 S(I,5)=Z
2416 A=S(I,0)
2418 B=S(I,1)
2420 C=S(I,4)
2422 GOSUB 1200
2424 S(I,0)=X
2426 S(I,1)=Y
2428 S(I,4)=Z
2430 NEXT
```

```
2440 FOR I=1 TO 32
2445 IF I>15 AND I<28 THEN 2495
2450 A=S(I,0)
2455 IF S(I,1)<1 THEN 2495
2460 K=0
2465 GOSUB 1400
2470 S(I,1)=S(I,1)-X
2475 A=S(I,2)
2480 K=2
2485 GOSUB 1400
2490 S(I,3)=S(I,3)-X
2495 NEXT
2496 RETURN
```

SUBROUTINE 2500---Displays all non-zero data in S(I,J).

```
2500 ! %10I,J,%12F1,S(J,1),%12F1,S(J,3),%12F2,S(J,4),
2501 ! %8F2,S(J,5)
2505 J=J+1
2510 IF J>32 THEN RETURN
2515 IF S(J,1)>1 THEN 2500
2520 RETURN
```

SUBROUTINE 2600---Converts RA/DEC into radians.

```
2600 R=(P1+P2/60)*.26179939
2605 D=(P3+P4/60)*.017453293
2610 D5=(J8-11544)/365.25636
2615 A=2.2347E-4*D5
2620 B=9.7171E-5*D5
2625 X=A+B*SIN(R)*SIN(D)/COS(D)
2630 Y=B*COS(R)
2635 X=R+X
2640 Y=D+Y
2645 IF X<0 THEN X=X+6.2831853
2646 IF X>6.2831853 THEN X=X-6.2831853
2647 RETURN
```

SUBROUTINE 2650---Calculates sidereal time for starting address.

```
2650 A=(P1+P2/60)*.26251617
2655 B=(J8-5234.5)*.017202124
2660 T5=A+B+.0741844
2670 IF T5>0 THEN 2680
2675 T5=T5+6.2831853\GOTO 2670
2680 IF T5<6.2831853 THEN 2690
2685 T5=T5-6.28311853\GOTO 2680
2690 RETURN
```

SUBROUTINE 2700---Airmass calculation.

```
2700 X=H\Y=SIN(G)\Z=COS(G)
2701 I=1
2702 GOSUB 2770
2705 X=T3\Y=SIN(T4)\Z=COS(T4)
2725 FOR I=2 TO 15
2730 IF S(I,1)<1 THEN EXIT 2745
2735 GOSUB 2770
2740 NEXT
2745 X=T1\Y=SIN(T2)\Z=COS(T2)
2750 FOR I=28 TO 32
2755 IF S(I,1)<1 THEN EXIT 2766
2760 GOSUB 2770
2765 NEXT
2766 RETURN
2770 H1=T5+(S(I,0)-T6)*.72921150E-4
2775 H=X-H1
2780 M=1/(.560643*Y+.82805767*Z*COS(H))
2785 S(I,2)=M*(1-.0012*(M*M-1))
2790 RETURN
```

SUBROUTINE 2800---Calculation of extinction coefficients and standard star readings using a linear least-squares fit to standard star data.

```
2800 X0=S(28,2)
2805 FOR I=28 TO 32
2806 K=I
2810 IF S(I,1)<100 THEN EXIT 2830
2815 NEXT
2820 K=K+1
2830 IF K>29 THEN 2852
2835 K1=.200\K2=.149\K3=.017\K4=-.041
2840 V0=-1.0857362*LOG(S(28,1))
2845 B0=-1.0857362*LOG(S(28,3)/S(28,1))
2850 RETURN
2852 G=0\Z=0\H=0\P=0\F1=0\F2=0
2854 FOR J=28 TO K-1
2856 X=S(J,2)
2858 A=-1.0857362*LOG(S(J,1))
2860 B=1.0857362*LOG(S(J,1)/S(J,3))
2862 G=G+A\Z=Z+A*X
2864 H=H+B\P=P+B*X
2866 F1=F1+X\F2=F2+X*X
2868 NEXT
2870 N=K-28
2872 D=N*F2-F1*F1
2874 Y=(G*F2-F1*Z)/D
2876 K1=(N*Z-F1*G)/D
2880 V0=Y+K1*X0
2882 Y=(H*F2-F1*P)/D
2884 K2=(N*P-F1*H)/D
2886 B0=Y+K2*X0
```

```
2888 K3=.017
2889 K4=-.041
2890 K2=K2-K4*M2
2891 K1=K1-K3*M2
2892 RETURN
```

Statements 3000 through 3370 write the final output data, including memory addresses, on a single 8 1/2 x 11 page.

```
3000 LINE #2,132
3005 INPUT "VARIABLE NAME ",N$
3006 INPUT "DESIG: ",B$
3010 INPUT "DATE OBSERVED (M/D/Y):",D$
3015 INPUT "DATA FILE/DISK NO. ",F$
3020 INPUT "ADDRESS FILE/DISK NO. ",G$
3021 ! #2,TAB(43),CHR$(14),N$,"  ",B$
3022 ! #2\! #2
3025 ! #2,N$,%5I,Q1,"H",%5F1,Q2,"M",%5I,P3,"D",
3030 ! #2,%5F1,P4,"M    ",D$,"    ",F$,"  ",G$
3035 ! #2
3040 ! #2,"      STANDARD STAR:  V=",%7F3,M1,"  B-V=",
3045 ! #2,%6F3,M2,%7I,R1,"H",%5F1,R2,"M",%5I,R3,"D",%5F1,R4,"M"
3050 ! #2
3060 Y=M1+K1*X0
3065 X=10^(.4*(16-Y))
3070 N0=S(28,1)/X
3075 ! #2,TAB(5),"Kv'=",%6F3,K1,"  Kv''=",%6F3,K3,"  Kvb'=",
3080 ! #2,%6F3,K2,"  Kvb''=",%6F3,K4,"    JD=244",%6F1,J8
3085 ! #2,TAB(10),"X0=",%7F3,X0,"    N0(16TH MAG)=",%7F3,N0,
3090 ! #2,"  EPS=",%6F3,E,"  MU=",%6F3,F
3091 ! #2,TAB(10),"STARTING ADDRESS: ",A$,"     PST FOR",
3092 ! #2,"START ADDRESS: ",%3I,P1,"H",%5F1,P2,"M"
3093 ! #2,TAB(23),"STAR #1:",%5I,S1,"H",%5F1,S2,
3094 ! #2,"M",%5I,S3,"D",%5F1,S4,"M"
3095 ! #2\! #2
3096 ! #2,TAB(32),"STAR RESULTS"
3100 ! #2,"STAR   NAME      Mv       V        B-V        Nv    ",
3105 ! #2,"    Nb          X     DV    DB"
3120 ! #2
3125 FOR I=1 TO 15
3130 IF S(I,1)<1 THEN EXIT 3155
3135 GOSUB 500
3140 ! #2,%2I,I,"            ",%9F3,M,%8F3,V,%8F3,B,%11F1,S(I,1),
3145 ! #2,%11F1,S(I,3),%8F3,S(I,2),%5F2,S(I,4),%5F2,S(I,5)
3150 NEXT
3155 ! #2\! #2
3159 ! #2,TAB(13),"BACKGROUND AND STANDARD(MINUS BKD) VALUES",
3160 ! #2,"(CTS/S)"
3165 ! #2,"PT#    V(STD)     B(STD)     DV    DB      X           ",
3170 ! #2,"V(BKD)    B(BKD)     DV    DB"
3171 ! #2
3175 FOR I=1 TO 5
3180 J=I+27\K=I+16
3181 IF S(J,2)>10 THEN S(J,2)=0.
3185 ! #2,%2I,I,%11F0,S(J,1),%10F0,S(J,3),%5F2,S(J,4),
3190 ! #2,%5F2,S(J,5),%8F3,S(J,2),%13F1,S(K,1),%9F1,S(K,3),
3191 ! #2,%7F2,S(K,4),%5F2,S(K,5)
3195 NEXT
3200 ! #2\! #2
3210 ! #2,TAB(30),"DATA ADDRESSES"
3215 ! #2,"STAR  V-ADDRESS       B-ADDRESS          PT.NO",
3220 ! #2,"    V-ADDRESS       B-ADDRESS"
3221 ! #2
3225 GOSUB 2000
3230 K=16
3235 FOR J=1 TO 15
3240 K=K+1
3241 IF K>32 THEN K=32
3245 IF S(J,0)>1 THEN 3260
3250 ! #2,TAB(43),
3255 GOTO 3295
3260 ! #2,J,
3265 FOR I=0 TO 3
3270 X=S(J,I)
3275 GOSUB 1100
3276 IF I<>2 THEN 3280
3277 ! #2," ",
3280 ! #2,"   ",A$,
3285 NEXT
3290 ! #2," ",S(J,4),"      ",
3295 IF K>27 THEN 3315
3300 IF S(K,0)>1 THEN 3325
3305 ! #2,"   STANDARD STAR ADDRESSES"
3310 K=27\GOTO 3360
3315 IF S(K,0)>1 THEN 3325
3320 ! #2\GOTO 3360
3325 ! #2,K,
3330 FOR I=0 TO 3
3335 X=S(K,I)
3340 GOSUB 1100
3341 IF I<>2 THEN 3345
3342 ! #2," ",
3345 ! #2,"   ",A$,
3350 NEXT
3355 ! #2," ".S(K,4)
3360 NEXT
3370 RETURN
```

TABLE 7. AN UMA 105845

AN UMA 11H 4.4M 46D 9.0M 3/20-21/82 SW-AN/D30 S20/D30

STANDARD STAR: V= 4.670 B-V= -.015 10H 54.0M 43D 12.0M

Kv'= .198 Kv''= .017 Kvb'= .150 Kvb''= -.041 JD=2445049.8
XO= 1.066 NO(16TH MAG)= 7.839 EPS= -.041 MU= 1.046
STARTING ADDRESS: 9274 PST FORSTART ADDRESS: 23H 56.0M
STAR #1: 10H 43.0M 46D 10.0M

STAR RESULTS

STAR	NAME V / B-V	Mv	V	B-V	Nv	Nb	X	DV	DB
1	5.18 / .33	5.094	5.184	.330	134377.0	751420.9	1.090	.03	.02
2	5.048/.611	5.006	5.044	.613	151748.4	669570.9	1.071	.02	.02
3	9.1	9.041	9.097	.520	3642.9	17378.7	1.073	.05	.02
4	11.9	12.006	12.037	.651	241.3	1030.6	1.079	.21	.09
5	#1 (~15.5)	15.615	15.568	1.085	9.2	27.0	1.099	.39	.33
6	#2	14.582	14.601	.720	22.6	90.7	1.104	.44	.21
7	#2 (new V)	14.529	14.536	.788	23.9	90.7	1.108	.49	.21
8	#3	14.015	14.071	.514	37.0	176.2	1.122	.35	.19
9	#4	13.577	13.611	.636	56.0	240.2	1.143	.31	.16
10	#5	13.465	13.499	.638	61.9	265.2	1.151	.34	.19
11	12.7	13.094	13.056	1.034	91.6	280.4	1.162	.26	.11
12	11.4	11.674	11.547	1.519	359.9	731.9	1.166	.15	.08
13	11.4 (repeat)	11.673	11.547	1.519	357.7	724.8	1.200	.13	.09
14	12.7 (repeat)	13.091	13.059	.997	90.6	284.8	1.205	.27	.17
15	11.0	11.124	11.051	1.230	569.7	1470.3	1.215	.08	.06

BACKGROUND AND STANDARD(MINUS BKD) VALUES(CTS/S)

PT#	V(STD)	B(STD)	DV	DB	X	V(BKD)	B(BKD)	DV	DB
1	219571.	1647166.	.02	.01	1.066	33.8	115.4	.77	.29
2	212418.	1553863.	.02	.02	1.248	36.7	121.6	.46	.30
3	0.	0.	.02	.02	.000	40.1	129.7	.45	.22
4	0.	0.	.02	.02	.000	.0	.0	.45	.45
5	0.	0.	.02	.02	.000	.0	.0	.45	.45

DATA ADDRESSES

STAR	V-ADDRESS		B-ADDRESS		
1	96F2	9728	9736	9766	50
2	982C	985C	97CA	9802	50
3	98B2	98E0	98F2	991E	.5
4	99BA	9A00	9962	99AE	.5
5	9D56	9DD8	9CB2	9D20	.5
6	9E2E	9E92	9F70	9FE0	.5
7	9EB4	9F1C	9F70	9FE0	.5
8	A0C6	A132	A054	A0A4	.5
9	A394	A3F8	A2EA	A34E	.5
10	A4AA	A4EA	A52E	A55E	.5
11	A5E4	A63C	A5A0	A5DE	.5
12	A66E	A6B2	A6EA	A712	.5
13	A9EC	AA38	A986	A9E0	.5
14	AA78	AAB6	AAC2	AAFC	.5
15	AB6E	AB9C	AB22	AB5A	.5

PT.NO	V-ADDRESS		B-ADDRESS		
17	9A56	9B6C	9B78	9BFE	.5
18	A146	A1C6	A1D8	A244	.5
19	A87E	A8E4	A8EE	A962	.5
STANDARD STAR ADDRESSES					
28	9682	96BC	961E	964E	50
29	ABE8	AC26	AC92	ACE0	50

REFERENCES

Blanco, V. M., *et al* (1974) Photoelectric Catalog, Pub. U.S. Naval Observatory, Vol. XX, Part VII.

DuPuy, D. L. (1981) "An Integrated-Circuit Pulse Amplifier For Use With Photomultipliers", P.A.S.P. 93, 144.

Hall, D. S. and Genet, R. M. (1982) Photoelectric Photometry of Variable Stars, I.A.P.P.P., Section 5-2.

Hardie, R. H. (1962) Astronomical Techniques, Univ. Chicago Press, 178.

Johnson, H. L. (1963) "Photometric Systems", Basic Astronomical Data, Univ. Chicago Press, 204.

Priser, J. B. (1794) "UBV Sequences in Selected Areas", Pub. U.S. Naval Observatory, Vol. XX, Part VII.

Rotondi, E., *et al* (1979) "Self-checking of Count Losses on Pulse Measuring Systems", Nuclear Instruments and Methods, 161, 459.

Stanton, R. H. (1981a) "Photoelectric Measures of AAVSO Comparison Star Sequences - II", J.A.A.V.S.O. 10, 1.

Stanton, R. H. (1981b) "Star Brightness Measurement Using Photon Counting". J.A.A.V.S.O. 10, 21.

West, J. B. and Bradford, R. S. (1975) "A Crystal-Controlled Oscillator For Telescope Drives", Sky and Telescope, Vol. 50, No. 2, 125.