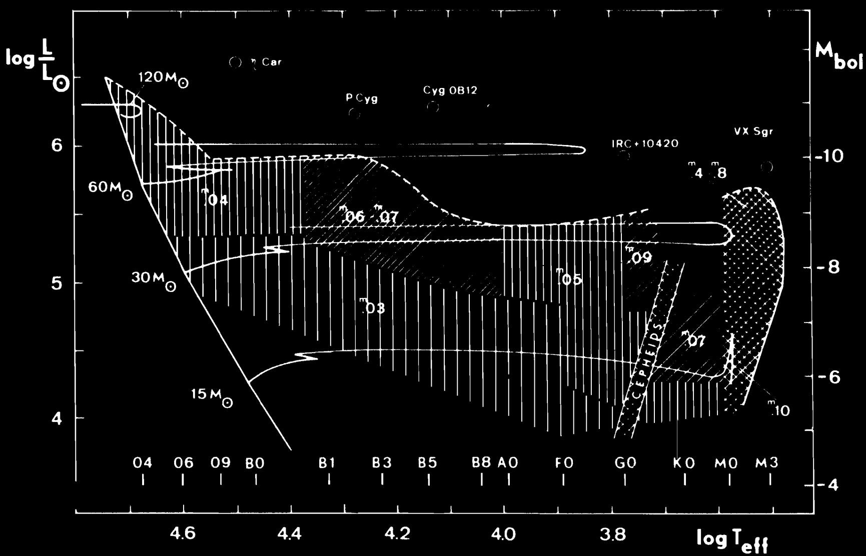
ADVANCES IN PHOTOELECTRIC PHOTOMETRY Volume 2



Editors

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ADVANCES
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PHOTOELECTRIC
PHOTOMETRY
VOL. 2

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PREFACE

This book is the second in a series of books which are being privately published in order that professional and amateur astronomers who are interested in photoelectric photometry, may both read what advances other astronomers have made in this field, and describe what advances in this area they have actually made themselves.

Photoelectric photometry is perhaps the most rapidly evolving branch of modern astronomy, and it is an area where an amateur astronomer can make (and has made!) extremely important contributions to the scientific community. What actually constitutes an "Advance" is quite difficult to describe. Obviously much of Volume 1 and this Volume would not be called "state-of-the-art photometry" (although some chapters could be). But that is not the purpose of this series of books. Any book which attempted to do such would soon be "out of date". We are simply attempting to provide an outlet which will reveal the current state of the science as it exists in today's universities, colleges, and privately owned backyard observatories. We have found the individual contributions which describe their advances in photoelectric photometry to be extremely interesting and enlightening, and it is our hope that you, the reader, will feel the same way.

Volume 2 is a truly international volume, with contributions from Australia, Hungary, Canada, People's Republic of China, U.S.S.R, Switzerland, and the United States. The first five chapters describe various new aspects in current photoelectric photometry; including a chapter by Dr. Dennis Dawson, "Light Pollution and its Measurement", which is destined to be the reference guide for persons interested in this area of photometry. Chapter 6 continues with the subject of small automated telescopes where Chapter 12 of Volume 1 leaves off. Much has happened in this area within the last year, and the editors expect that automated telescopes will revolutionize the field of photoelectric photometry within the not too distant future.

The last five chapters each describe photometry as it is being done at a different location around the world.

We have tried to make several improvements in Volume 2 which we felt were needed after reading Volume 1 -- not the least of which was the small type size of Volume 1! We are sorry about that and hope that the eye strain was not too severe. But we all learn by experience, and we hope that Volume 3 will be even better than Volume 2.

Robert C. Wolpert
July 4, 1984

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WHY DO WE PREFER PHOTOELECTRIC PHOTOMETRY?

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I. INTRODUCTION

A favorite pastime of many amateur astronomers is the observation of variable stars. The observation of a variable star is always an uplifting and fascinating experience. As far as the casual observer is concerned, the stars in the heavens shine unchangeably, and once upon a time, this was a long-lasting, common belief. However, patient and persistent astronomers have in modern times revealed the light variation of some stars with the naked eye. There is no doubt at all that visual observations have rendered a great service to the development of our knowledge, and even today when we investigate the behavior of a star, we often open the old publications in order to use the visual observations. Although old, these data are very important in describing the puzzling history of stars.

The development of improved observational techniques paved the way for the discovery of a great number of new variable stars of different types. In addition to the classical variables (e.g. Miras and novae), several very strange kinds of variables are known which have changed the classical notion of variable stars. For example, an X-ray variable may be constant in the optical wavelengths, or, to take another case, line profile variables can hardly be detected by broad-band photometric observations.

Despite the great service of visual observations in the past, they do not fulfill the present day requirements. Many persons claim that variable stars with small amplitude (such as Beta Cephei and Delta Scuti stars) are the proper objects for photoelectric studies, and visual observations of the variables with large amplitudes can furnish valuable data. Without denying the usefulness of visual observations in certain cases (e.g. Miras), there are a number of phenomena in large amplitude variables which can be studied only by photoelectric photometry. In fact, these phenomena usually have very interesting astrophysical bearing on stellar structure and evolution. Even though these effects are often minute, they are by no means negligible, and very important conclusions can sometimes be drawn from them.

In the following examples we would like to illustrate that photoelectric observations made with simple equipment are able to make a major contribution to our knowledge. We mainly concentrate on variable stars of the instability strip but with just a quick glance at some other types. The importance of the photoelectric observations of small amplitude pulsating variables has already been discussed by Percy in the first volume of this book.

II. LARGE AMPLITUDE VARIABLE STARS

The large amplitude Delta Scuti (or dwarf Cepheid) stars have often been recommended to visual observers. The rapid increase in brightness and the sharp maximum make the observations easy. However, a word of warning is appropriate here: the observational errors are usually underestimated and thought to be less than 0.1 in the height of maximum and from 3 to 4 minutes in the timing of the maximum. In reality, the usefulness of visual observations is questionable because their accuracy is not sufficient. By using the timing of maxima, it is possible to check the period changes by constructing the phase diagram. The period changes of dwarf cepheids may be due to various effects. For example, SZ Lyncis, a well-known dwarf cepheid, was discovered to be a component of a binary system as a result of its phase diagram being analyzed. Figure 1 shows how the period of SZ Lyn varies with time. The photoelectric observations clearly outline the light-travel-time effect due to the binary motion. Since the total amplitude of the waves in the phase diagram is about 0.01 day, the required accuracy in timing should be better than 0.002 day, which can be achieved only by photoelectric techniques. The published visual observations are also plotted in Figure 1. It can be seen that these points in the phase diagram do not suggest that the waves are superimposed on a parabola, which means that the pulsation period has a slight continuous increase. Even such fundamental parameters as the orbital period and the value of v.sin i can be determined from this diagram.

Other large amplitude Delta Scuti stars, e.g. YZ Bootis or DY Herculis, also show linearly changing periods with a very low rate. These changes may have an evolutionary origin and/or maybe connected with processes altering the stellar structure. It is very important to observe these minute changes in the period, but this would be a hopeless task for visual observers.

A number of dwarf cepheids exhibit double mode pulsation. The co-existence of the two periods in the same star results in a strongly modulated light curve. Accurate values of the periods and any possible changes in them can be determined only if a large amount of photoelectric data is available. A few of these double mode dwarf cepheids are bright enough to be observed with a moderate size telescope. Figure 2 shows a part of the light curve of AE UMa obtained with a 50 cm telescope equipped with a conventional UBV photometer at Konkoly Observatory. Some of them (e.g. VZ Cancri in the northern hemisphere, V 703 Scorpii and SX Phoenicis in the southern hemisphere) are well within reach of a very small telescope.

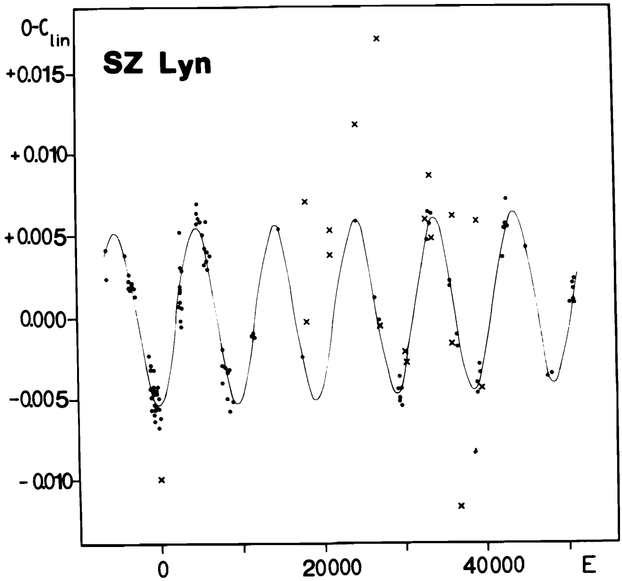

Fig. 1: Phase diagram of SZ Lyn. Dots indicate photoelectric observations, crosses denote visual ones obtained by experienced observers. (The visual O-C's are mean values taken from well-known astronomical journals.)

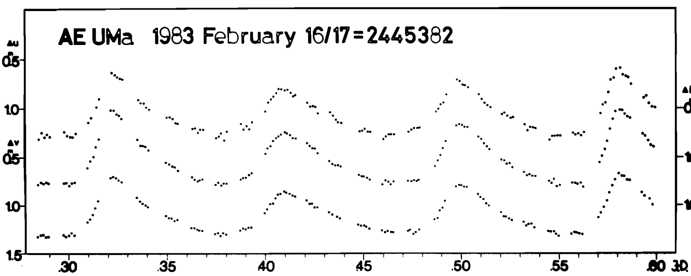

Fig. 2: UBV light curves of AE UMa

III. RR LYRAE TYPE STARS

The RR Lyrae type stars are old favorites of visual observers. These stars pose a number of interesting problems; one such problem is the period change. Visual observations enable the rough behavior to be followed. In the last few years, however, the fine structure of the phase diagram has become a very important matter and fine details can be studied only by photoelectric observations. It is still an open question whether the changes in the period are continuous or abrupt. The phase diagrams of the RR Lyrae stars exhibiting the Blazhko effect are especially complicated. About 30% of the RR Lyrae stars do not have a stable light curve, i.e. the light variation itself has a non-repetitive character. The light curve of a single periodic RR star can be described by the period, the shape of the light curve (asymmetry), the amplitude, and the color indices at certain phases. Some RR Lyrae stars show striking changes in their parameters during a long (40 to 80 days) secondary period. The height of maximum may undergo a change of some 0.1 to 0.2, and the phase of maximum oscillates with the same long period. The amplitude of the oscillation can sometimes reach an hour. This phenomenon was first observed visally by Blazhko in RW Draconis and XZ Cygni. Soon, other stars were suspected of having the same effect. Curiously, Sperra stated that both SU Draconis and SW Draconis showed the Blazhko effect on the basis of visual observations, whereas photoelectric observations do not reveal any light curve variation in these particular cases. Several visual observers have claimed the existence of the Blazhko effect in a number of stars (for instance AT And and AN Ser) but as soon as these stars were observed photoelectrically their light curves proved to be stable. A plausible explanation for this controversy might be that the Blazhko effect used to be present in these stars and later on it ceased. These results, however, should be handled cautiously as, strangely enough, it has never happened that a single periodic, photoelectrically observed RR Lyrae star has become a multiple periodic or vice versa.

The determination of the secondary periods by visual observations has often led to contradictory results: unambiguous values of the periods can be obtained only when using photoelectric observations.

Regular photoelectric observation of RR Lyrae stars exhibiting the Blazhko effect is of great importance because the physics of the phenomenon is not yet clear.

Recently, double mode pulsation was also discovered in RR Lyrae stars. These stars pulsate in the fundamental and in the first harmonic mode. Several double mode RR Lyrae stars are known in globular clusters, but only one in the field (AQ Leonis). A very interesting star is BV Aquarii, with a fundamental period of 0.364 day. Tsesevich placed this star among the RR Lyraes showing the Blazhko effect with a secondary period of 11.6 days. This longer period may be incorrect; if so, BV Aqr might belong to the group of double mode RR Lyraes. This particular star is strongly recommended to photoelectric observers.

IV. CEPHEID VARIABLES

Cepheid variables are also favorite targets for variable star observers. Due to their high luminosity and low galactic latitude, a number of nearby classical cepheids can easily be seen with the naked eye. The early visual observers did a tremendous amount of work: a good portion of our knowledge about the period changes of these variables is based on their records. Now, however, most of the photometric data on cepheids are photoelectric, and it must be admitted that the present visual estimates of their brightness are much less valuable than they used to be.

Professional astronomers are interested in conducting very detailed research on the chemical composition of cepheids and the well-known relationships which are valid for these stars. To this end only selected stars (e.g. calibrating cepheids) are observed and the majority of the bright cepheids tend to be ignored. In order to follow their period changes to construct phase diagrams, regular photoelectric observations of cepheids are necessary. This work can be performed even with the simplest photoelectric photometers.

Figure 3 shows the phase diagram of the prototype star Delta Cephei where triangles, filled circles, and open circles denote the residuals based on photoelectric, photographic, and visual observations respectively. The size of these symbols refers to the weight of the respective observational series. Although the visual observations are able to outline the parabolic trend of the curve, i.e. the continuous period decrease, the photoelectric points show much less scatter around the fitted curve. Any subtle phenomenon in the phase diagram such as the effect of duplicity (which is not so rare amoung the cepheids) can be noticed only when using photoelectric observations.

In the case of Delta Cephei the decrease in the period is as small as 10 seconds in a century, but even so, it is noticeable. Since it is the period that can best be determined among the characteristic parameters of a variable star, the period changes are good means of tracing the secular variations in a star, i.e. the stellar evolution. Thus a photoelectric observer can watch how a cepheid crossed the instability strip without any visible change in the luminosity or the temperature (color index) of the star. Similarly, the observation of double mode cepheids would be very valuable. The group of beat cepheids consists of a dozen known members: the brightest stars with more than one period being TU Cas and U TrA. The photometric data on these stars are so scanty that it is no wonder that controversial statements about their behavior can sometimes be found in the literature. We do not know exactly whether the amplitudes of the two co-existing modes remain constant or whether they vary in an observable time-scale. This mode-switching is a basic theoretical problem of the double mode pulsators. The period changes in these stars are also worth study. Any such study, however, would tax even the most patient observer.

It is much simpler to examine the stability of the light curve of single periodic cepheids. A long series of photoelectric observations made with the same equipment would be very valuable and it might well result in revealing secular light curve variations.

The above suggestion is even more valid for the Population II cepheids. Although the short period group of these latter variables (BL Herculis stars) has been observed frequently enough, the same cannot be said of the long period group (W Virginis stars). The W Vir stars have a very unstable period and are suspected of changing their light curve. In this respect, these stars are similar to RV Tauri variables whose even and odd (epoch number) light curves are different from each other.

As we go further to the right from the instability strip we find variable stars with lower temperature and less regularity. Several of these semi-regular variables are fairly bright and are within the reach of small telescopes. Most of the information we have about their light variations comes from visual observations. Since the amplitude of these stars is usually less than one magnitude, the uncertainties of the data are relatively high. The fact of the uncertainties is supported by our own photoelectric observations.

At the beginning of the seventies we started observing several SRd variables at Konkoly. One of the program stars was VW Draconis. In the papers of the visual observers it had often been reported that the star had light variation with an amplitude of some tenths of a magnitude and a period of about several months. A great number of photoelectric observations were connected at Konkoly Observatory and no definite sign of light variability in VW Draconis could be detected (see Figure 4). The same result was obtained by Murnikova and Vasilyeva in 1979. One can only say that it would be rather peculiar if the star were to be constant when observed photoelectrically and variable duing the period of visual observations. This example also clearly shows the importance of photoelectric photometry.

The observation of R CrB variables has remained the hunting ground for visual observers. The moment of ingress into the sudden deep minimum is unpredictable, therefore the alert provided by visual observers is very useful. Even so, some of these stars also deserve the attention of photoelectric observers. The R CrB variables situated in the instability strip (i.e. with F or G type spectra, however rich they are in carbon and helium) are pulsationally unstable and do pulsate with an amplitude of several tenths of a magnitude. RY Sgr and R CrB itself are the best known stars illustrating this phenomenon. For both stars the cycle length of the pulsation is about 40 days.

Dwarf novae are yet another favorite type for visual observers. In this case their task is to count all the outbursts. One subtype of these variables, viz. the SU UMa stars, is subjected to small amplitude oscillations (superhumps) in the phase of superoutbursts. The superhumps are well worth being observed photoelectrically. Their characteristic amplitude is several tenths of a magnitude, whereas the period is as short as several hours.

In addition to the objects and phenomena mentioned above, the microvariables, the spotted stars, the eclipsing binaries, and other objects (see the respective chapters in the first volume of this book) offer a rich choice for those photoelectric observers who wish to contribute to our knowledge of variable stars.

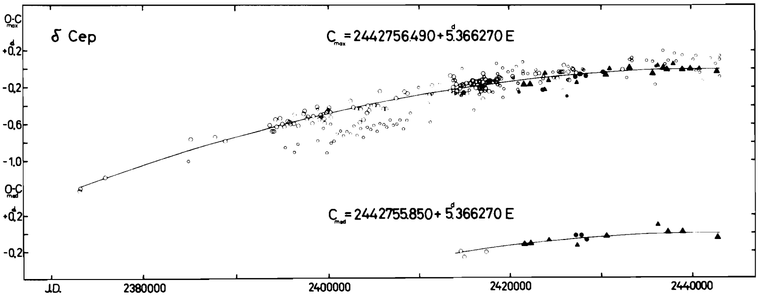

Fig. 3: O-C diagram of δ Cep

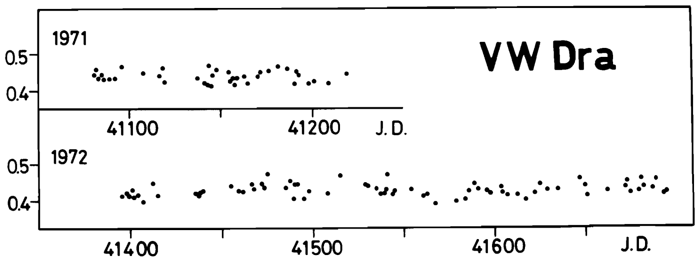

Fig. 4: ΔV observations of VW Dra. The error of a single observation is about 0.02 magn. If any variations exist, its amplitude should be less, than 0.05magn.

2

DESIGNING AND IMPLEMENTING A PHOTOELECTRIC PHOTOMETRY PROGRAM: THE AAVSO EXPERIENCE

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I. INTRODUCTION

As a reader of this book, you are probably already aware of the valuable research which can be carried out with a small telescope equipped with a photometer. The equipment can be quite modest: a 6" telescope will suffice, and a photometer can be purchased for a few hundred dollars, or built for much less. If you have access to such equipment, then this chapter is addressed to you. It tells about a new photometric research program in which you can participate: the American Association of Variable Star Observers (AAVSO) Photoelectric Photometry Program (PEPP).

The program may appeal to the following groups (among others): (1) active photometrists looking for new stars to observe, (2) active visual observers of variable stars wanting to expand into photoelectric photometry, (3) amateur* astronomers who have built or purchased a telescope and are looking for something interesting and worthwhile to do with it, or (4) college instructors or students looking for challenging projects for a "teaching telescope". All of you have one great advantage over those of us who use photometric telescopes at the remote national observatories such as Kitt Peak and Cerro Tololo: you have a "backyard observatory" (so to speak) which is available on any clear night. You can therefore carry out long-term monitoring of variable stars with moderate to long time scales. Hundreds of bright stars fall into this category.

II. WHY A PHOTOELECTRIC PHOTOMETRY PROGRAM?

A photoelectric photometry program is a set of variable stars which is to be observed in a specified way, usually relative to a specified set of comparison stars. Many photometrists are already in a position to choose the variable stars which they observe, either as a result of their association with an individual astronomer (usually a professional) or a group. These photometrists can most likely reduce their own observations, and analyze and publish them through existing channels. For them, a new photoelectric photometry program is something which they can take or leave.

Other photometrists, active or prospective, may choose

* The term "amateur" is used in the sense discussed by Williams (1983): Someone who carries out an activity with a high level of skill but not for remuneration.

for various reasons to participate in a program (like the AAVSO-PEPP) which is designed and coordinated by others. Such an arrangement has certain advantages, especially for beginners: (1) there is some guarantee that the work being done is worthwhile, (2) there is a knowledgeable program coordinator to provide advice, encouragement and assistance, (3) a few good observations from each of many observers can be combined into a densely-covered light curve (i.e. "the whole is greater than the sum of its parts"), and (4) there is an intangible sense of belonging when one works with a group.

III. WHY ANOTHER PHOTOELECTRIC PHOTOMETRY PROGRAM?

There is no shortage of stars in need of photoelectric photometry. Aside from the many self-designed programs which amateur and professional observers carry out, there are several existing photoelectric photometry programs. Most of them are built around a specific class of "microvariables" (Percy, 1983), and all of them are scientifically productive.

(1) RS Canum Venaticorum stars are binary stars containing at least one "active" solar-type star: one with spots, chromosphere, radio flares, and a hot X-ray emitting corona. The rotation of the spots in and out of the observer's view produces brightness variations, and long-term cycles in the spots cause these brightness variations to be irregular. A successful program of photometry of these stars has been designed and coordinated by Dr. Douglas S. Hall (Zeilik _et_._al_., 1979).

(2) Be (emission) stars are hot, rapidly-rotating stars which are surrounded by shells of gas which are sporadically emitted from the star (in most cases) by rotation, radiation, and possibly pulsation. These shells produce the spectral emission lines which give this class of star its name. They also produce long-term spectrum and brightness variations, the nature and cause of which are still not well understood. A program of long-term UBV photometry of bright Be stars has been designed and is being coordinated by astronomers at the Ondrejov Observatory in Czechoslovakia, under the auspices of the International Astronomical Union (Harmanec, 1983). Since the brightness variations are small, the observations must be made and reduced very carefully, and therefore this program is not recommended for beginners.

(3) Yellow supergiants are often variable with amplitudes of several tenths of a magnitude on time scales of weeks to months. As well as the regularly varying Cepheids, there are also less regular variables. Some have recently been subclassified into (a) "Leavitt variables": luminous stars like ρ Cassiopeiae with time scales $>$ 150 days, and (b) "UU Herculis variables": less well understood stars with time scales $<$ 150 days. The moderate amplitudes, long time scales, and irregularity make these ideally suited to backyard observatories (Percy, 1980).

(4) The AAVSO (among other groups) has longstanding programs of timing the minima of eclipsing variables and the maxima of Cepheid variables. These timings can be used to measure period changes, which in turn tell us about the evolutionary processes in these stars. A few observers are using photoelectric techniques to improve the accuracy of the timings and to study variables with small amplitudes.

This leaves many classes of microvariables open for study. If we eliminate the ultramicrovariable β Cephei, δ Scuti, and magnetic Ap stars because of the limitations of the observing conditions at most backyard observatories and because of the inevitable difficulty in intercomparing observations from different sources, we are still left with many opportunities. One obvious class is the Small-Amplitude Red Variables; these form the bulk of the AAVSO-PEPP.

IV. THE ORIGINS OF THE AAVSO-PEPP

More than a century ago, Dr. Edward C. Pickering, Director of the Harvard College Observatory, published a "Plan for Securing Observations of Variable Stars". In it, he pointed out the value of long-term observation of variable stars, as John Herschel and Friedrich Argelander had done earlier. (He also pointed out that this activity might appeal to women, a prediction which has been borne out by the great contributions which women have made to the study of variable stars and to the work of the AAVSO.) The AAVSO was established in 1911 to help carry out Pickering's plan. Indeed, one of the reasons for the success of the Association has been its worthwhile and well-defined purpose.

Although the AAVSO visual program has diversified over the years, long-period variables have always been the backbone of the program. These stars play many roles in the drama of stellar evolution. Virtually every star (including the sun) becomes a long-period variable (LPV) towards the end of its life. The most extreme LPV's are the Mira variables: cool giant stars which pulsate with periods of hundreds of days. Partly as a result of the pulsation, material streams off the Mira variables at rates approaching one solar mass per million years, profoundly affecting the evolution of the star. This material becomes part of the interstellar medium, where it becomes available for the formation of new generations of stars. LPV's are difficult to understand because the processes which take place within them (pulsation, convection, shock waves, mass loss) are processes which astronomers cannot easily model. Visual observations of LPV's are therefore of value, specifically for the following purposes: (1) to enable astronomers to know when the stars will be at maximum or minimum brightness so that observations may be planned accordingly, (2) to enable astronomers to know what the brightness of the stars actually were when their observations were made so that they can interpret them, (3) to monitor period changes which shed light on mass loss and other processes in the stars, and (4) to monitor irregularity in the light curves, which may be caused by shock waves, convection, or other processes.

The AAVSO-PEPP grew out of the AAVSO visual program of observation of LPV's. Although there are thousands of large amplitude LPV's, there are even more small amplitude variables: SARV's, as Olin Eggen has called them. There are dozens among the naked-eye stars, including η Geminorum, μ Geminorum, β Gruis, α Herculis, β Pegasi, and ρ Persei. These stars, which have not been intensively studied in the past, make up the bulk of the AAVSO-PEPP. Aside from the four purposes mentioned above, observations of the SARV's will provide basic information on their periodicity and regularity. It is also possible that the SARV's are intrinsically "simpler" than Mira variables, and will therefore yield information about themselves more easily.

V. SETTING UP THE AAVSO-PEPP

The preliminary choice of stars for the AAVSO-PEPP was made in 1981-1982 by the Director, Dr. Janet A. Mattei. Many of the stars were on the AAVSO visual program, but had amplitudes which were too small for accurate visual observation. Incidently, there are advantages in obtaining simultaneous visual and photoelectric observations of the same stars. The photoelectric observations can be used to check and calibrate the visual ones, and to look for and possible correct systematic errors in the visual observations due to differing color sensitivity of different observers' eyes. The visual observations can be used in some cases to fill in gaps between photoelectric observations, especially if they can be averaged to improve their accuracy.

It was at this point that I became involved with the program. I assisted Dr. Mattei in the final choice of stars, removing a few of the most "difficult" variables and adding a few "easy" ones of the RS Canum Venaticorum, Be, and yellow supergiant kinds. (As mentioned below, there are difficulties in observing red variables relative to non-red comparison stars.) The program is now in final form, and contains stars which are suitable for just about any site, instrument, and observer. From time to time, we may "retire" stars from the program as they become sufficiently well understood, and replace them with other stars. Another possibility is to extend the program to the program to the infrared R and I bands. Thus, the program will evolve just as the stars themselves do.

Photoelectric photometry can be done in an absolute way relative to a single set of standard stars spread across the sky, but this approach requires an experienced observer, a good sky, and a sophisticated reduction procedure. An easier approach is the differential one, in which each variable has two or more comparison stars relative to which it is observed. Every participant in a program uses the same comparison stars for a given variable; otherwise it is virtually impossible to inter-compare data from different observers.

Comparison stars should be of known constant magnitude and, ideally, near the variable in the sky in order to reduce differential extinction effects, and similar to the variable in magnitude and color to reduce gain and differential color effects. At least two comparison stars should be used so that the magnitude differences between them can be used to monitor their constancy and the quality of the data. In practice, it is difficult to find comparison stars with all of these characteristics. For example, comparison stars which are similar to red variables in color tend to red variables themselves! For this reason, choosing the comparison stars in a photoelectric photometry program is as crucial as choosing the variables themselves.

For the next few years, we will monitor the comparison stars in the AAVSO-PEPP carefully. We shall try to obtain some observations of them at a good site in an absolute way, so as to determine their UBV magnitudes more accurately, and to monitor their constancy. Inevitably, a few comparison stars will have to be discarded because they are variable (a useful by-product of the program!) and replaced by other comparison stars.

Participants in the AAVSO-PEPP are expected to observe the standard comparison stars for every variable which they choose. The observations must then be corrected for extinction and transformed to the UBV system. This will be done at AAVSO headquarters. In retrospect, implementing this system for reducing the observers' data was one of the most complicated and time-comsuming aspects of setting up the program. It is possible for the observers to reduce their own data, but experience with other photoelectric photometry programs indicates that the observers' reductions must be supervised very closely.

VI. STORING AND PUBLISHING THE OBSERVATIONS

Good observations deserve to be made available (or as Friedrich Argelander said: "data in a drawer are no data at all"). AAVSO visual observations are carefully edited and documented, and published from time to time as AAVSO Reports. The observations are increasingly becoming available in machine-readable form, and it is the goal of the Association to eventually have <u>all</u> observations so available. (I have recently made use of long-term visual observations of ρ Cassiopeiae and can vouch for the convenience of observations available in this form). Observations available <u>only</u> in this form have one disadvantage: the observers never get to see their observations plotted on a real light curve. There is merit in having observations available in <u>both</u> published and archival form, so there is still a place for the AAVSO Reports, costly though they are.

Visual observers of LPV's are aware that many decades may pass before their observations bear fruit, and are therefore patient and understanding as far as the analysis of their observations are concerned. Photoelectric observers, on the other hand, are accustomed to seeing their observations analyzed and published more quickly. That is because the popular RS Canum Venaticorum program tends to produce results within a season or two, and the coordinator of this program has been prompt and efficient in the analysis and publication of these results. Rightfully so: observations which are worth making are worth publishing!

The AAVSO-PEPP may not yield results so quickly, although for some stars, a season or two of good, dense observations will suffice. Some preliminary results have already appeared (Landis, 1984). It will be our goal to continue to receive, edit, document, and publish the program observations as soon as is practical, just as in the case of the AAVSO visual observations. In that way, interested astronomers (including myself) can assist in the analysis of these observations, though Dr. Mattei has the overall responsibility for the supervision of the program.

VII. WHY JOIN THE AAVSO-PEPP?

Attracting observers to a new photoelectric photometry program is like attracting consumers to a new brand: there must be some motivation to switch! For the amateur observer, the motivation is not money or professional advancement. To some extent, it may be enjoyment, but whereas astrophotography and deep sky observing are usually done for fun, I know of no photometrists who observe for the sheer joy of counting photons. Ideally, the motivation is the satisfaction of contributing to astronomical knowledge. Participants in the AAVSO-PEPP can be assured of doing that. They will benefit from the advice and assistance of the coordinators and other observers. In time, they will see their observations published, and see intangible return on their investment of time and effort. They will also experience the intangible benefits of working with one of the world's most remarkable scientific associations, and continuing a tradition which began over a century ago.

VIII. HOW TO JOIN THE AAVSO-PEPP

Technically, you do not have to be a member of the AAVSO to participate in the AAVSO-PEPP, but we hope that you will want to be. To join the AAVSO-PEPP (or the AAVSO), simply write to the Association at 187 Concord Avenue, Cambridge MA 02138, and ask for any or all of the following:

(1) Observer Information Sheet: on this sheet you record the details of your site, instrumentation, and observing procedures so that we can document and reduce your observations.

(2) Observing Report Forms (with instructions): on these, you can record your observations in a standard format for reduction.

(3) AAVSO Photoelectric Photometry Chart Catalog ($1.00): this lists the individual charts which can be obtained (for $0.25 each), showing the variable, comparison stars, and surrounding field. There are also charts which show the standard stars which you may use to determine your transformation coefficients.

You may also write for general information about the program, which we are happy to provide.

Further information about the program is provided by the AAVSO Photoelectric Newsletter, of which I am presently the editor. The Newsletter has a circulation of several hundred copies, and contains information, news, progress reports, and preliminary results of the program. Members of the AAVSO can obtain the Newsletter free of charge. For non-members, there is a subscription charge of $5.00 per annum (three or four issues).

The American Association of Variable Star Observers' Photoelectric Photometry Program is young. We hope it is also pliable and destined for a long and successful life. We welcome comments and suggestions. Most of all, we welcome your support and participation in photoelectric photometry: the new frontier in small-telescope astronomy.

ACKNOWLEDGEMENTS

I thank Dr. Janet A. Mattei and the other members of the AAVSO who have contributed to the Photoelectric Photometry Program. I have appreciated and enjoyed their help and friendship. I also thank the University of Toronto and the Natural Sciences and Engineering Research Council of Canada for supporting my work in the AAVSO.

REFERENCES

Harmanec, P. (1983) Advances in Photoelectric Photometry 1, 42.

Landis, H. (1984) AAVSO Photoelectric Newsletter 4, #3, 3.

Percy, J.R. (1980) Journal of the AAVSO 9, 64.

Percy, J.R. (1983) Advances in Photelectric Photometry 1, 26.

Williams, T.R. (1983) Journal of the AAVSO 12, 1.

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

3

ALGOL BINARIES: VARIABLE PHOTOMETRIC DISTURBANCES AND EVOLUTION

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I. INTRODUCTION

The so-called "Algol paradox" kicked off the modern study of close binary evolution more than 20 years ago. Algols consist of fairly hot primary stars close to the main sequence, and evolved, cooler, less massive subgiant secondaries. The "paradox" is of course that the less massive star is the more evolved (the possibility that the subgiant is still contracting toward the main sequence was laid to rest years ago: there are simply too many of them). We resolve the paradox by assuming that the present secondary was once the more massive star, and has since transferred enough mass to the present primary to reverse the mass ratio. That the present secondary (but not the primary) essentially fills its Roche lobe supports the suspicion that even now, mass transfer may occur. To economize in syllables, I will use Plavec's simpler nomenclature of (mass) "loser" and "gainer" to specify these stars.

Algols are the offspring of an earlier stage of rapid mass transfer that reversed the mass ratio of the stars. Perhaps active binaries like β Lyr and the "Serpentid" binaries of Plavec are examples of this stage of rapid mass flow. These latter binaries are so complicated by circumstellar gas that the underlying stellar structure is poorly known. By contrast, the flows in Algols are much reduced and in fact are highly variable, so the stellar properties are fairly well known.

Their evolutionary state makes Algols prominent light variables. The subgiant losers are large and cool, so when the orbital planes are nearly in the line-of-sight, deep total primary eclipses occur. The ultraviolet eclipse of RW Tau is 5 magnitudes deep, and reduces the ultraviolet light to 1% of its uneclipsed value. During totality, only the light of the K subgiant loser is normally seen. Orbital periods of "short-period" Algols lie between ~ 1 and 5 days, and a good fraction of a primary eclipse can be observed in one night. As readers of IAPPP publications know, orbital periods of Algols can change, sometimes abruptly, and times of mid-eclipse can therefore be advanced or retarded. These times can be measured accurately by PEP, and their determination is one of the important contributions that amateur astronomers make to our science.

This short article is not a general review of Algols, but rather concentrates on variable photometric instabilities, some of which are within observational reach of amateur telescopes. I suspect that many of these instabilities are triggered by erratic mass flows from the lobe-filling loser. Such flows originate from the inner hemisphere of the loser. Matter streaming between the stars is gravitationally accelerated to speeds on the order of several hundreds of km/sec, and strikes the photosphere of the gainer in short-period systems. The high energy of this impacting stream is dissipated in the outer layers of the gainer, leading to all sorts of observable effects.

I want to write mainly about photometric effects, but I have to say that spectroscopy, particularly in the satellite ultraviolet, is a much better way to detect circumstellar gas in close binaries. Recently, several astronomers have used the IUE satellite to study high-temperature emission, or sometimes absorption, lines in many Algol binaries. These lines originate in a high-temperature, turbulent accretion layer spread along the gainer's equator. This layer must be powered somehow from the accretional energy brought in by the mass stream. Moreover, there is evidence that carbon is underabundant and nitrogen overabundant (relative to the sun) in such accretion layers - just the kind of abundance anomalies produced in stellar matter processed by the CNO nuclear cycle. This result is striking spectroscopic support for the general evolutionary picture described above.

What does photometry add to this picture? By "photometry" I mean broad - or intermediate-band photometry, using passbands much wider than the breadth of a spectral emission line. To produce a significant variation in such a passband requires a change in the continuum radiation; adding an emission line like Hβ will make very little difference, unless it is very strong. Such a change is said to be "optically thick" (i.e., opaque or nearly opaque) in the continuum. Familiar examples are the starspots of RS CVn binaries. The "change" must encompass enough matter to influence the continuum radiation. By contrast, the striking variations sometimes seen in ultraviolet emission lines occur in low-density circumstellar regions containing little matter. There is a fair analogy to the sun, where emission lines originate in a hot low-density chromosphere or corona, while the continuum radiation (or changes, as in sunspots) come from much higher-density photospheric regions. While photometry is unable to give us the dynamic details revealed by spectroscopy, it does signal quasi-photospheric changes involving appreciably more mass. These two observational techniques are complementary.

II. PHOTOMETRIC VARIATIONS IN ALGOLS

These are photometric changes detectable by photoelectric photometry (PEP), and often varying in a time as short as the orbital period. By a wide margin, they were most striking in the bright Algol U Cep, which I started observing in 1974. Most of the detailed discussion below deals with this system. I searched for similar variations in some 90 primary eclipses of 15 other bright Algols, from 1978 to 1981. As a result, RW Tau joined U Cep as a photometrically active binary. These systems have sometimes brightened in primary eclipse by more than a magnitude in the ultraviolet. Smaller variations, $\lesssim 0.1$ mag, were noted in RZ Cas and U CrB. In every case, changes were seen in all five passbands used (Strömgren-Crawford uvby, and Kron I), confirming that they were continuum (~ photospheric) effects probably related to intermittent mass flows. Primary eclipse light curves of U Sge were sometimes systematically brighter or fainter than normal by as much as ~ 0.3 mag, a unique behaviour in my experience. It looks as though one or both stars in this binary are slowly varying in radius. More observations, within and outside eclipse, will be needed to verify this explanation, and I will not discuss it further here.

Algol mass flows triggering photometric variations are highly irregular. We do not yet know the causes or all the time scales that modulate such flows, even in the best-observed case, U Cep. The thousands of hours of observation required to clarify these variations, as well as to search for them in other bright Algols, would require ground-based photometry with moderate-sized telescopes. Ideally, such telescopes would be automatic photoelectric telescopes (APT's) used in a program lasting at least 5 years.

Now, I will summarize some of the activity that nearly 10 years of observations has unearthed in U Cep.

III. A DECADE OF U CEPHEI

This bright Algol ($V \sim 7$) has been known for over 100 years. The component stars are B7V + G5-8 III-IV, and the orbital period is 2.493 days. That period is gradually increasing, but this binary also suffers abrupt period increases/decreases every few years (as do most Algols). The hot star (gainer) spectrum is never quite normal, and has absorption lines broadened by rapid rotation ($\sim$ 300 km/sec). Emission lines of hydrogen have been observed from time-to-time for about 50 years, but were most prominent and intensively observed during the very active years of 1974 and 1975. We now know that large photometric distortions are present when emission lines are strong. Normal primary eclipses are total for about 2 hours (between second and third contacts, t_2 and t_3). Quiescent light curves are never completely clear of photometric distortions, but look tame compared to their active, distorted counterparts. Photometric distortion can occur at all orbital phases. Figure 1 shows the geometry of U Cep.

a) Primary Eclipse.

When distorted by intermitted mass flows, the normally total primary eclipse can become an asymmetrical partial eclipse, particularly at short wavelengths. Figure 2 shows this effect and its change with time. We can analyze the "extra light" (i.e., the "disturbed" minus "undisturbed" light) at all 5 wavelengths, from ultraviolet to near-infrared. The result is always the same: at internal contacts, there is extra light of photospheric origin and effective temperature slightly below than that of the undisturbed gainer photosphere. It is easy to show that the gainer has sprouted an asymmetrical equatorial bulge: the star has become "pregnant". The bulge seems to be highest near t_2, or more accurately, in the region where the stream strikes the gainer. The equatorial effective radius has increased by $\sim$ 25%, and the bulge distorts the surface between latitudes $\sim \pm 45°$. We have observed the bulge to collapse and disappear in as little as two orbital cycles.

In a detailed analysis of such distorted light curves, one can trace the light added by a hot spot on the gainer, and a light loss at early ingress phases where the stream is seen projected against the gainer's photosphere (Olson 1980a, 1980b). Note also that during eclipse after phase $\sim$ .03, there is a light loss in disturbed eclipses. Later, I will relate this loss to other losses observed outside primary eclipse.

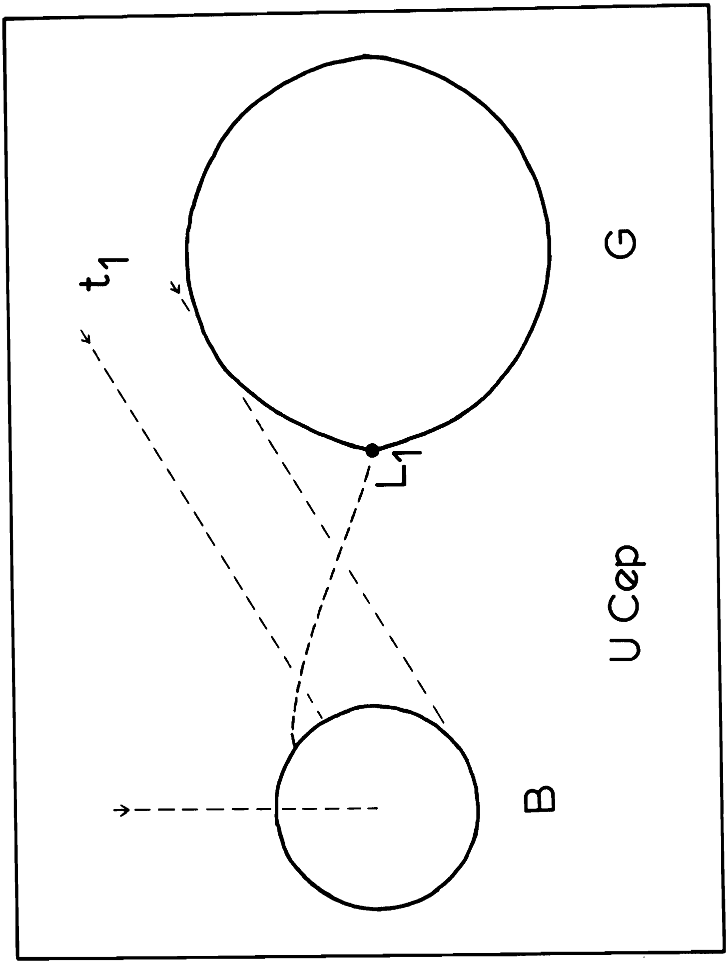

Fig. 1. The Algol system U Cep, viewed from above the orbital plane. The stars can be thought of as fixed, with the observer revolving around the B star in the clockwise sense. The sight line for phase 0.75 is vertically downward, and two parallel sight lines shown are for first contact of primary eclipse, t_1 (since this binary's orbit plane is not exactly edge-on, the actual geometry for t_1 is slightly different). The curved dashed line approximates the center of the mass-transferring stream, which starts around the "inner Lagrangian" point L_1 on the inner surface of the G loser.

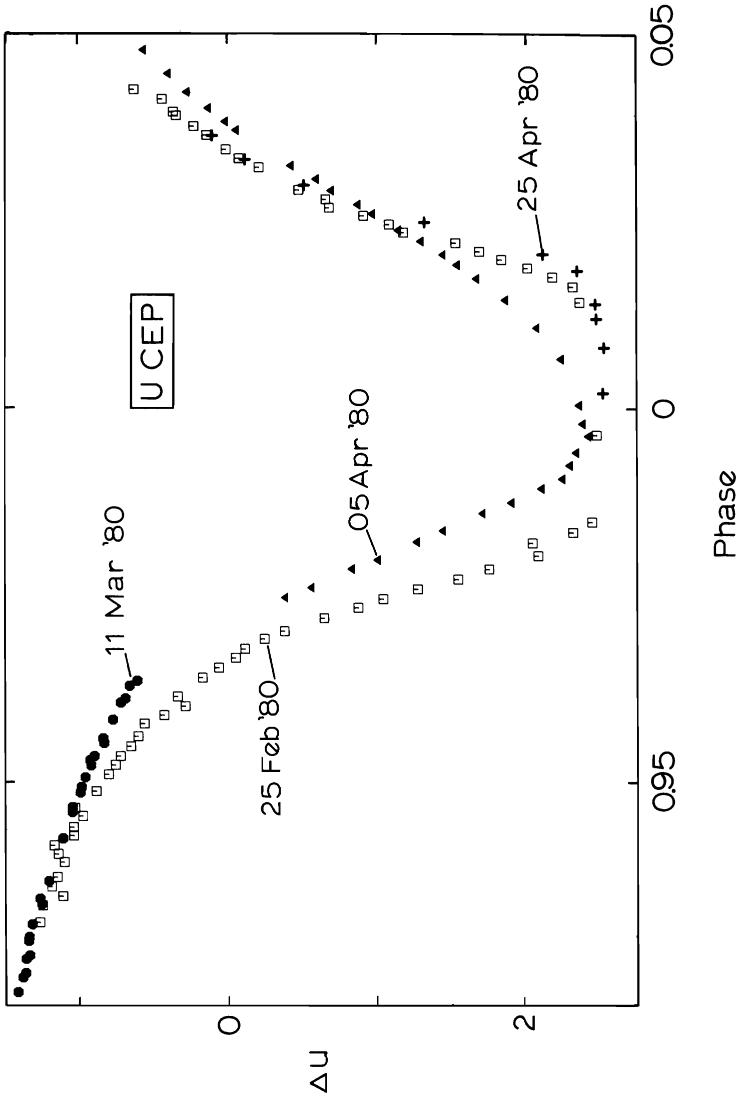

Fig. 2. Light curves of U Cep in the Strömgren-Crawford ultraviolet. Curves on 25 Feb. and 25 Apr. are relatively undisturbed, while those of 11 Mar. and 5 Apr. are distorted by mass-transfer activity. In the most-disturbed eclipses so far observed, excess ultraviolet light at t_2 (near phase 0.98) amounted to 2 mag.

Figure 3 shows y observations of a number of primary eclipses in 1974. Qualitatively, they show the same features as Figure 2. In addition, they indicate that the cool star (more accurately, its outer hemisphere) changes in brightness by ~ 0.1 mag. This variation had been known earlier, and was variously explained as "chromospheric variations" or the presence of "circumstellar material". It is neither, as multi-color observations show. The color of the G-star variation identifies it as photospheric in origin. When brighter than normal, the G star's photosphere warms by a few hundred K. I will show later that these warmings are intimately correlated with the presence of mass flows.

b) Outside Primary Eclipse.

When U Cep is undisturbed by mass flows, the typical interactive effects of "reflection" and "tidal distortion" are apparent outside eclipse, particularly at long wavelengths. When disturbed by mass flows, however, much larger irregular distortions appear outside eclipse, and the light level falls. Losses are progressively larger toward shorter wavelengths, and in u the light curves become truly bizarre (Fig. 4). Moreover, they share the time variability, and are contemporary with, light excesses seen in primary eclipse and losses seen near the end of primary eclipse. They have been seen only in U Cep (the three-year survey mentioned above included only a few points outside primary eclipses).

At first thought, for the luminosity to fall during periods of mass flow makes no sense: it should increase because of extra accretional energy that must be radiated away. So, what mechanism can explain the large apparent loss, particularly near phase 0.6? First, this loss is purely in the continuum. On several occasions, I have made narrow-band $H\alpha$ and $H\beta$ observations outside eclipse. While these indices do vary, there is no correlation with the intermediate-band losses. Second, the cool star cannot be implicated, as its contribution to the total light is tiny compared to out-of-eclipse losses. Third, suppose magically that we could decrease the area of hot star to produce a light loss. The light indeed would fall, but the magnitude drop would be the same at all wavelengths; we need a mechanism that drops the light more at shorter wavelengths. Part of the normal photosphere needs to be replaced by a cooler region. I will not call it a "spot", because I doubt that magnetism plays any role in its formation. If it were a spot, though, it would dwarf any known star spot.

The light loss at phase 0.6 in Figure 4 can be modelled extremely well by replacing about 3/4 of the projected radiating hemisphere with a "refrigerated" region about 3500 K cooler than the normal photosphere ($\sim 13{,}000$ K). This model can best be checked by referring to the drop in light near phase 0.6 that occurred between 25 and 30 October (1975; see the lower panel in Fig. 4. Treating the loss differentially removes uncertainties in undisturbed levels at this phase). This differential loss is ~ 0.35 mag in u, and is progressively less toward larger wavelength. I have shown the observed losses, expressed as monochromatic fluxes ΔL_{λ}^{c}, as the solid broken lines in Figure 5. The error spread is due mostly to the millimag errors in the differential magnitudes. Circles are fluxes from the "cool region" model, calculated using theoretical fluxes from Kurucz

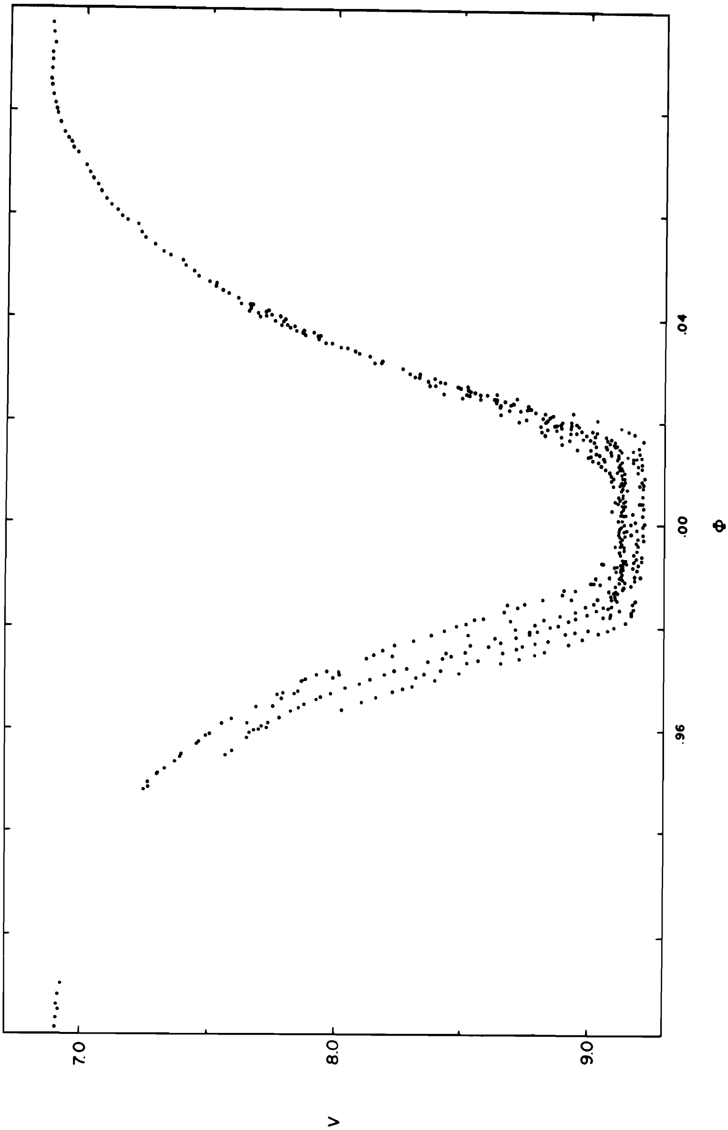

Fig. 3. Visual light curves of U Cep during the fall of 1974. Courtesy of the University of Chicago Press.

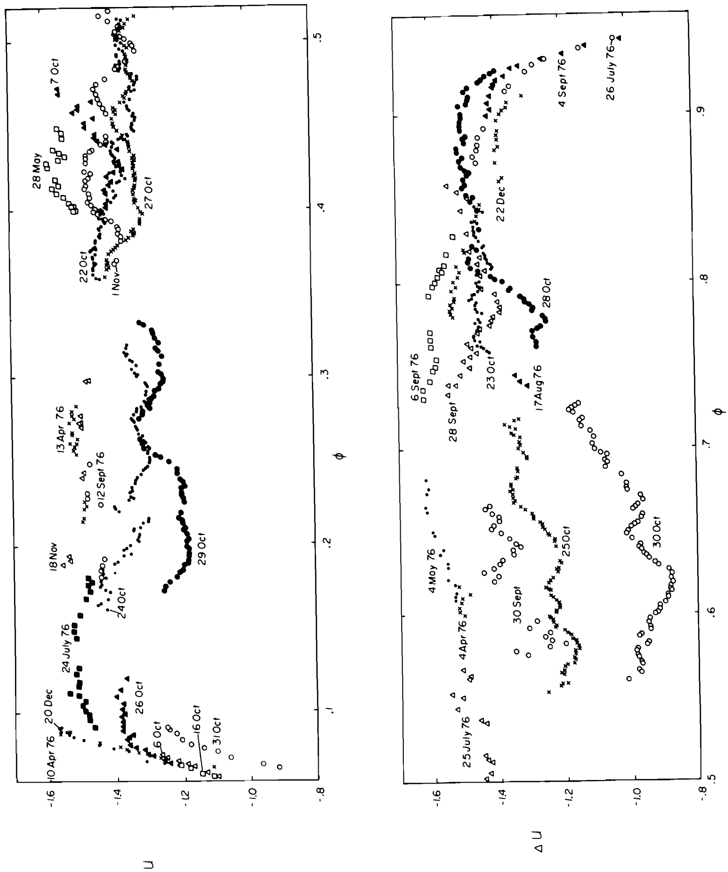

Fig. 4. Ultraviolet light variations outside primary eclipse in U Cep (unless otherwise noted, the year was 1975). In late October 1975 the loss grew rapidly, particularly near phase 0.6, where the ultraviolet light dropped to about half of its normal value. Upper left and lower right panels include a bit of primary eclipse. Courtesy of the University of Chicago Press.

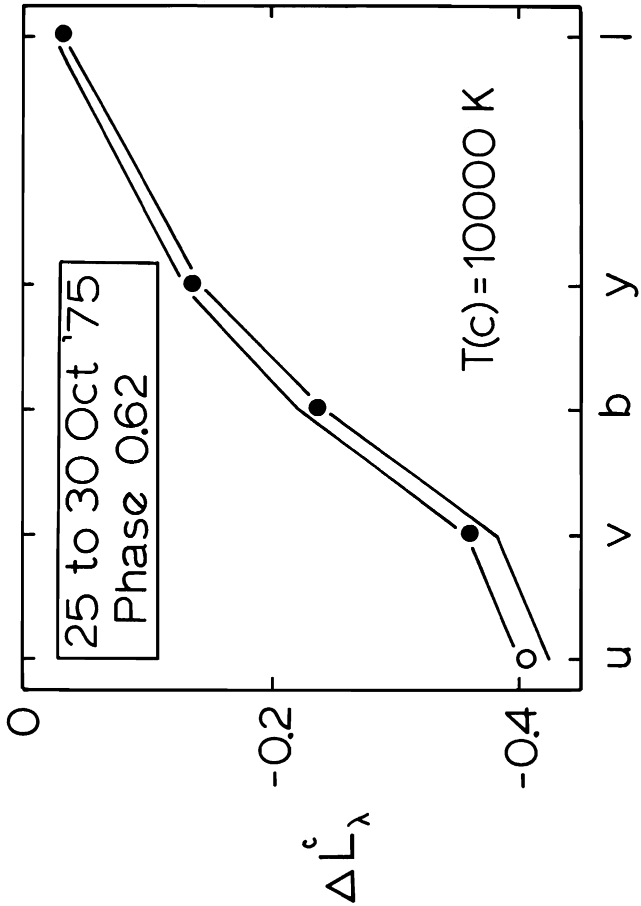

Fig. 5. The spectral flux distribution of the light drop between 25 and 30 October 1975, at phase 0.62. The broken full lines give the observational error spread. Symbols are theoretical losses for the "cool region" model explained in the text.

model atmospheres. I think there is little doubt that this is a successful model.

A large apparent light loss at a time of enhanced mass flow can be understood using the "equatorial bulge" that was evident during primary eclipse. Suppose that the highest point of the bulge is not above the hot spot as I implied earlier, but faces the phase 0.6 direction. The bulge is cooler than the undisturbed photosphere, but it's presence increases the total photospheric radiating area. A rough calculation shows that such a bloated star can increase its luminosity at the same time that the energy radiated near the orbital plane actually drops. In other words, the excess luminosity due to accretion is radiated away normal to the orbit plane, and all of the observations are consistent qualitatively.

c) Speculations.

We are a long way from verifying this picture theoretically. There is no computer capable of following the hydrodynamical effects of hypersonic stream impact on the gainer. A few things are clear. Most of the streaming matter penetrates deeply below the gainer's photosphere. Only in the low-density outer fringes of the stream might the material be stopped or even "spread" along the photosphere to form the hot accretion region revealed by ultraviolet spectroscopy. The energy of the deeply-penetrating material is largely dissipated into radiation and perhaps turbulence, increasing the radiation pressure and producing equatorial bulges. I have suggested that if these bulges are close to quasi-hydrostatic equilibrium, then their large vertical extent (top to bottom, roughly half the gainer diameter) cannot be achieved without the aid of radiation pressure support. But these are hand-waving, order-of-magnitude assertions that still lack real physical support.

That the equatorial bulge is asymmetrical, with more mass above the following than above the leading hemisphere of the gainer, has been verified in every disturbed eclipse so far observed. In other words, the presence of mass transfer induces some unknown degree of mass asymmetry in the gainer. The only way I know to estimate this asymmetry is to find the mass contained in the bulges using the assumption that they are in hydrostatic equilibrium normal to the orbit plane. Such estimates are rough, and I will not give any numbers here (see Olson et al 1981). Suffice it to say that if these masses are of the right order, and if mass transfer were not erratic but more nearly continuous as it might have been earlier in evolution, then these asymmetrical bulges could have played an important role in that evolution.

There are at least two problems in calculating the theoretical evolution of close binary systems with mass flow. When mass flows: (1) does some of it fail to be captured by the gainer, and leave the system?; (2) how is the orbital angular momentum affected? From spectroscopy we do know that some mass can leave the system, possibly decreasing the orbital angular momentum. The balance of these losses helps to determine the evolution. For example, loss of orbital angular momentum alone would drive the stars closer together, accelerating mass flow and evolution. The precise path that a close binary follows through the phase of rapid mass transfer on the way to the Algol state is unknown. Certain assumptions must be made in theoretical calculations. The simplest is the "conservative" case: that total mass and orbital angular momentum remain constant. But this assumption is probably inadequate.

The mass asymmetry induced in the gainer in U Cep by mass flows causes the loser to exert a gravitational torque on the gainer. This torque is in the sense to slow the gainer's rotation, thereby increasing the orbital angular momentum of the binary. A similar situation exists in the evolution of the earth-moon system, where ocean tides give the earth a mass asymmetry. The reason for this asymmetry is of course entirely different from that in U Cep. If the numbers I mentioned above are roughly correct, and if peak mass flows that we now see in U Cep ($\sim 10^{-6}$ solar masses/year) were more nearly continuous in earlier stages of evolution, then this torque would be an important factor in keeping the evolving stars apart, thereby tempering the rate of evolution. This suggestion is more speculative than the earlier ones. It may well be wrong, but it does suggest the potential value of persistent and detailed observations of selected Algols. If some very complicated and specific mechanism like this <u>were</u> important in early binary evolution, then realistic evolutionary calculations would become still more difficult.

d) Variations with Time.

Having summarized some of the photometric fluctuations and their interpretations, I will next describe briefly how they vary with time. I'm convinced that we have now observed most of the photometric tricks this system can play on us in optical radiation. The time dependence of these effects may offer more clues to help us to understand better the activity in this system.

We saw in Figure 2 that during active intervals U Cep brightens considerably before and after primary eclipse totality. I've defined an "activity criterion" (AC) which is linear with this excess ultraviolet light, and which can be specified consistently at any of several orbital phases between 0.96 and 0.02. It varies from 0 (undisturbed) to 1 or slightly greater (highest level of disturbance, approaching a 2-mag brightening at t_2). This index over the last 9 years is plotted in the upper panel of Figure 6. The irregular, almost eruptive, nature of mass flows in U Cep is obvious. Well-observed groups of distorted eclipses occurred in late 1974 and 1975 (centers of the "eclipse window" in the U.S.). An expanded plot of the former would show you that mass flows responsible for this activity varied on a time $\sim$ 20 days. Longer characteristic time scales undoubtedly enter, but the approximate rate of 7 eclipses observed per year fails to reveal them. It is obvious however that the fraction of relatively undisturbed eclipses went up after 1975.

The lower panel of Figure 6 shows fluctuations in the brightness of the outer hemisphere of the G-star (observed during the truly "flat" parts of primary eclipse totality). "Flashes" of G-star brightening are superimposed on a slow (cyclical?) brightness change. In at least 5 cases, in 1974, 1975, 1980, and 1983, flashes correlated with large AC (in a few other cases, the G-star was not observed). It is this flashing phenomenon that caused the change in

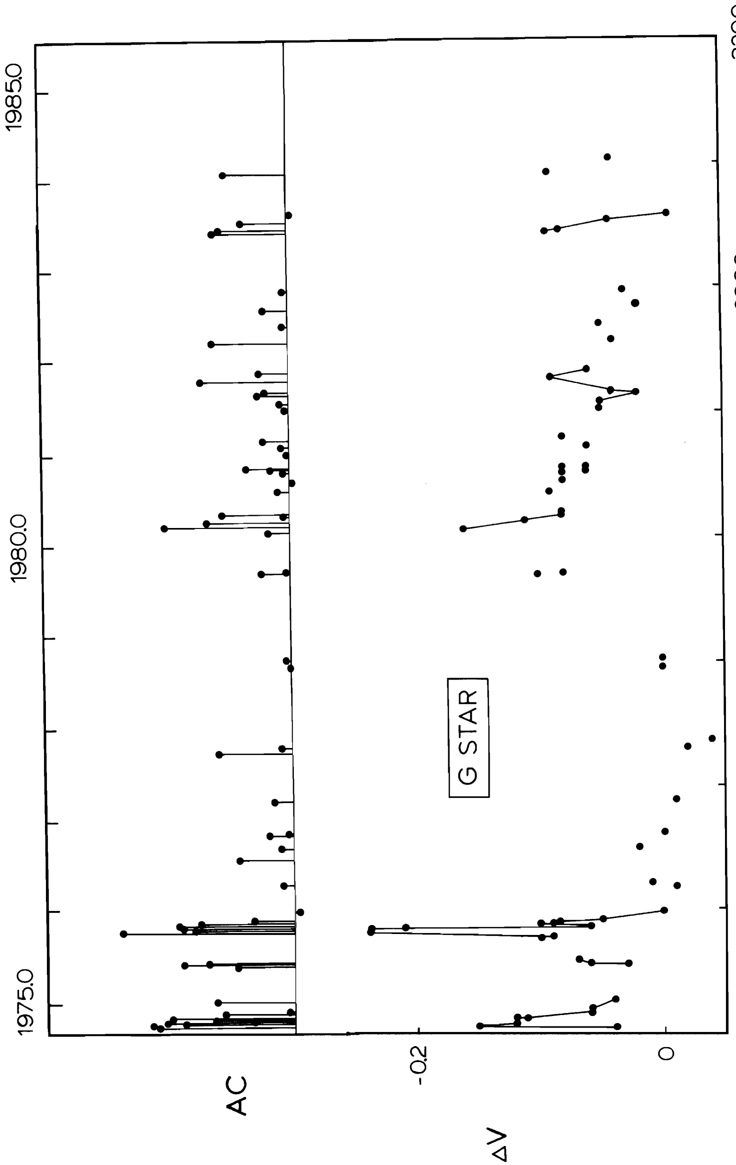

Fig. 6. Activity in U Cep over the past nearly 10 years. The upper panel gives AC, the "activity criterion", which measures the excess ultraviolet light in distorted primary eclipses. The lower panel shows visual magnitude variations of the outer hemisphere of the G loser, measured during primary eclipse totality. Brightness "surges" and the slow underlying variation are discussed in the text.

totality level of Figure 3. This is our only evidence that the G loser is linked to photometric activity in U Cep.

It is not difficult to see a possible reason for such G-star brightening. Suppose that the outer (convective) part of the G star suffers an instability, perhaps of the sort that Bath has studied theoretically for a number of years, that causes matter to flow upward through its photosphere. Since the G star fills its Roche lobe, this matter could then flow along the Roche surface to the so-called "inner Lagrangian point" L_1 at the inner sub-stellar point, to join the stream of matter flowing toward the gainer (see Fig. 1). In the convective region below the photosphere of the loser, the most abundant element, hydrogen, is largely ionized. Flowing through the photosphere, hydrogen ions recapture free electrons to become neutral, releasing energy (13.6 electron volts per atom). This freed ionization energy causes the star to brighten. Knowing the normal G-star luminosity, we can easily calculate the hydrogen recombination rate required to brighten the G star by the observed amount, roughly 0.1 mag. If the effect is uniform over the G star's surface, the rate is 4×10^{-6} solar masses/year. This figure is consistent with peak flow rates found from properties of the distorted gainer, so our picture is at least self-consistent. The G star appears to be the origin of mass flows that trigger everything else.

There remains the underlying slow quasi-cyclic brightness change of amplitude $\gtrsim 0.05$ mag (and period ~ 6 years?). I suggest that this is produced by an RS CVn-like migrating wave; that is, that the loser is spotted preferentially in one hemisphere, and that this hemisphere slowly migrates relative to the stellar line of centers. We cannot see the "S-wave" over one orbital cycle because the G-star is seen only during 2-hour primary eclipse totality. We must wait for the migration itself to vary the spot number seen at totality. A cycle in the actual spot number could further modulate the G star brightness, but as Hall (1984) has pointed out, such cycles have not really been recognized in RS CVn binaries. The loser in U Cep has other properties consistent with the presence of spots: chromospheric activity is seen in variable emission in the H and K lines, and X-rays possibly from a G-star corona have recently been detected. This star is also a rapid rotator, a condition favorable to magnetic activity and spots. I want to emphasize that all the variations shown in the lower panel of Figure 6 were caused by photospheric changes in the G star. I have some evidence of a similar slow change of brightness in the K loser of RW Tau, the other Algol that shows photometric disturbances similar to those of U Cep. Other Algols are being checked for such variations.

If spots and strong localized magnetic fields are really present in the G loser of U Cep, then another possibility arises: that the erratic mass flows are partly magnetically triggered. With bipolar spots come magnetic flux tubes arched above the photosphere, and directing the flow of matter. Suppose that such magnetic arches were rooted on the inner hemisphere of the loser; they could perhaps increase the mass-transfer rate by feeding extra matter directly into the stream near L_1. Enhanced flows and larger photometric disturbances would therefore be seen when the spotted hemisphere of the loser faces away from earth at primary eclipse. In such an orientation, the G-star would be at the peak brightness of its slow variation. The most pronounced events, judged by the AC, have in fact occurred near such orientations (in 1974, 1975, 1980), but the limited data available now hardly prove the association. Some years of continued observation remain to clarify these issues.

I mentioned orbital period changes in §I and III. Since 1972, U Cep has undergone four abrupt period changes of alternating sign. It was natural to assume that these period changes were produced by sudden mass flows and changes in orbital angular momentum. Sudden flows surely occur, but they are not associated with period changes. The latter must be produced by some other subtle independent mechanism, like internal density distribution changes in the loser, as proposed by Matese and Whitmire (1983). We do not know, of course, if the same holds true for the many other Algols with abrupt period changes. This, too, is a matter requiring more observations.

IV. FINAL COMMENTS

Nearly a decade's worth of photometry of U Cep has uncovered a fairly rich display of activity. Primary eclipses of RW Tau have shown smaller photometric disturbances that mimic those of U Cep, except that no evidence is seen of a light loss outside eclipse. Those losses in U Cep were the largest changes in light units (not magnitudes) seen. In the picture I sketched earlier, these outside-eclipse losses were caused by the distorted equatorial bulge around the gainer, and I further argued that such bulges could have real evolutionary significance. We know of their existence only in U Cep. Were I to try another photometric survey of short-period Algols, I would be tempted to spot systems between secondary and primary eclipses in an effort to find such losses. I would certainly include ultraviolet observations, because such losses are greatest at short wavelength. Such a program would then be rather like the successful monitoring of RS CVn variables -- except that in most cases, there would be only null results. But the eventual discovery of other systems with the "bulge syndrome" could help to clarify its possible role in close binary evolution. Such a search is after all an attempt to view stellar evolution in real time, and those who lack the required "sitzfleisch" need not apply!

I won't try to acknowledge all those who have helped and encouraged this observational effort. The basis for the study of activity in U Cep was laid about a decade ago by Drs. Alan Batten and Doug Hall. Dr. Mirek Plavec has offered encouragement and suggestions, and directed the doctoral research of Dr. Dick Crawford on hydrogen emission lines in U Cep. Dick was later my post-doc at Illinois, and together we have chewed over most of the puzzles posed by U Cep. The National Science Foundation supported most of this research, and observations were done at Prairie Observatory (Illinois), Kitt Peak National Observatory, and Mount Laguna Observatory (San Diego State University).

REFERENCES

Hall, D. S. 1983, Advances in Photoelectric Photometry 1, 18.
Matese, J. J., and Whitmire, D. P. 1983, Astr. Astrophys. (Letters) 117, L7.
Olson, E. C. 1980a, Astrophys. J. 237, 496.
_____ 1980b, Astrophys. J. 241, 257.
Olson, E. C., Crawford, R. C., Hall, D. S., Louth, H., Markworth, N. L., and Piirola, V. 1981, P.A.S.P. 93, 464.

4

LIGHT POLLUTION AND ITS MEASUREMENT

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I. The Problem of Light Pollution

Riegel (1973) has called light pollution "unwanted sky light produced by man because of population growth and increased outdoor illumination per capita". To people who carry out astronomical observations near urban areas, and to anyone who has seen and appreciated a truly dark sky, the above abstraction has become an unpleasant reality.

Who has not seen the murky, discolored night skies above the larger cities? At the best times – say, after the passage of a thunderstorm, when much of the particulate matter in the air has been precipitated – a city dweller may be able to barely glimpse a few of the fainter naked-eye stars. But, even such a view will be a poor version of the skies that used to be visible from those same cities, just a half-century ago. People have been removed from the splendor of the heavens by a shroud of light and dirt.

Possibly the worst aspect of the light pollution problem is that, in many cases, it need not be as bad as it is. What is seen illuminating the sky, benefitting no one, is energy that could be profitably redirected. The most important step in controlling light pollution is one of education: making the public and municipal governments aware of the advantages of EFFICIENT lighting use. Sperling (1980) has discussed some of the more notable successes and failures in this area.

Brightening night skies have created more specific problems for observational astronomers. A high sky background imposes limits upon the useful photography of faint stars or faint details in extended objects (e.g., spiral arms in galaxies). For spectrographers, the night sky has become "spectrally dirty": streetlight emissions are interfering with the recording and interpretation of subtle features in the spectra of distant stars, nebulae, and galaxies. For photometrists, a bright sky means having to deal with TWO significant sets of observational (Poisson) statistics, setting an effective limit to the accuracy of sky subtraction from the photometry of faint stars. For any astronomical observations, the overall effect of a bright sky is to reduce a telescope's ultimate performance.

Despite the perceived extent of the problem, quantitative data on light pollution are surprisingly sparse. Yet, such data prove very useful for adjusting the thrust of observing programs, locating darker sites, and demonstrating energy waste. In the sections that follow, the procedures for obtaining such data, and using them to gain a better understanding of the problem, are discussed.

II. History of the Problem

Why has light pollution become such a serious problem? Certainly, some of the contributing factors are socioeconomic. Increased lighting seems consistent with increased economic prosperity, greater leisure time, and the lifestyles (including more night business and recreational activity) that accompany them. Criminal activities will also often increase under such conditions, and increased lighting is frequently viewed as necessary for discouraging the overt side of such activities and facilitating identification of their perpetrators. It might be said, by some, that light pollution is a necessary price for living in a high-technology society.

(a) The Evolution of Lighting. Important as the above considerations are, the present situation stems MOST directly from the development, and subsequent inefficient use, of very efficient types of lighting. Much of this lighting was developed in the decades following the second World War.

Table 1 lists the major lighting types now in common use. Lamps are usually rated in "lumens per Watt", a sort of efficiency (the actual term is luminous efficacy) comparing the lamp's visible-light output with the electrical power (input) that it uses. The maximum luminous efficacy of a lamp – that of a white-light source which could be made to radiate uniformly over the response range of the daylight eye (about 5000-6200 Angstroms) – is about 220 lumens per Watt; modern lamps are, therefore, approaching their theoretical capabilities.

Table 1 Ratings for Common Lamps

Lamp Type	Efficacy (lumens/Watt)
incandescent (tungsten)	17-35
fluorescent	35-85
mercury vapor	37-56
deluxe mercury[1]	28-62
multi-vapor[2]	85-115
high-pressure sodium	95-140
low-pressure sodium	137-183

Information sources: General Electric publication TP-109R (1975), North American Philips Lighting Bulletin SOX-100 (1972)

1 "Deluxe" mercury vapor lamps have an interior fluorescent coating that absorbs mercury's ultraviolet emission and re-radiates it as visible light.

2 Multi-vapor (or metal-halide) lamps are mercury lamps that also contain iodides of sodium, indium, thallium, and/or scandium. They vaporize at different operating temperatures and provide very efficient fluorescence mechanisms.

Modern lamps have long lifetimes (typically 10,000-20,000 hours) and give good nighttime color renditions of people and vehicles. Unfortunately, the processes which have improved the visible-light outputs of lamps have also made the effects of streetlight emissions very hard to filter. Figure 1 displays the emissions from some of the lamps of Table 1. Mercury vapor lamps have a number of important emissions in the blue spectral region, including two (4078 and 4358

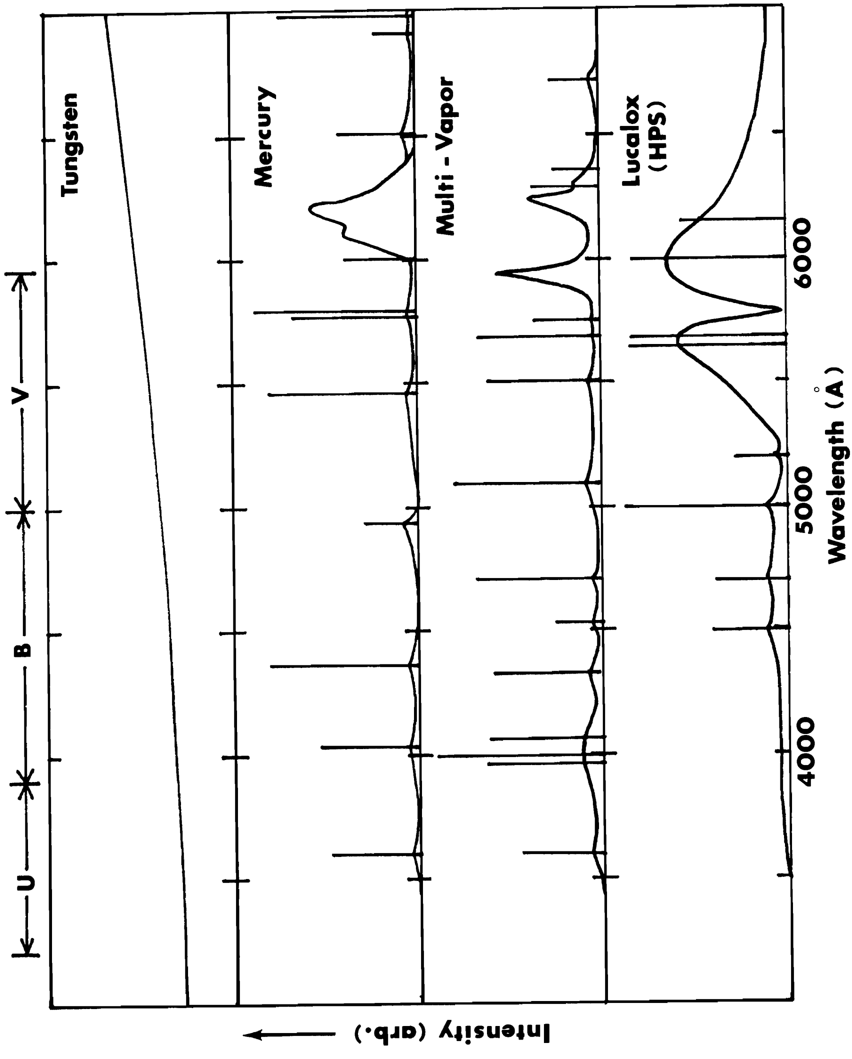


Figure 1 — Visible energies emitted by some common lamps. The vertical intensity scale is arbitrary; the absolute and relative intensities of the emission lines and the continuous spectra can depend upon the lamp's operating voltage. The approximate wavelength ranges of the U, B, and V filters are shown at the top.

Angstroms) that lie near important stellar spectral features (the line Sr II 4077, whose strength is sensitive to stellar luminosity, and H-gamma 4340 of the hydrogen Balmer series). Multi-vapor lamps tend to be very "spectrally dirty" because they combine the emissions from several different chemical species. In high-pressure sodium (HPS) lamps, light from the sodium "D" lines is redistributed into a surrounding continuous spectrum; there is little light remaining at the original wavelengths (5890, 5896 Angstroms) of the D lines. Low-pressure sodium (LPS) lamps emit light primarily at the wavelengths of the D lines, and this light can be easily filtered, but their intense yellow-orange color has occasionally been considered objectionable.

With the more efficacious lighting, a lot of "free illumination" became available, especially following the early 1960's. There was not, however, much concomitant growth in the use of better shielding, better filtration (when possible), or careful lamp placement techniques. Some of this lack may be laid to the economic prosperity of the 1960's: energy conservation measures were not pursued as vigorously as they have been in more recent years.

(b) Astronomical Studies of Light Pollution. Astronomical awareness of the problem seems to have begun in earnest around the early 1960's, although some of the larger observatories (such as Mount Wilson Observatory near Los Angeles) had been following their local lighting increases with some concern for decades earlier. In central, coastal California, the growth of population and lighting in the Santa Clara Valley (San Jose and its neighboring towns) began to noticeably affect the limits for accurate photography and photometry of faint objects at the Lick Observatory on nearby Mount Hamilton. Walker (1973) provided photometric evidence that the night sky's brightness in the direction of San Jose had increased by about 0.05 magnitude per year between 1948 and 1972. He also showed that spectrograms taken at Lick between 1960 and 1972 were increasingly contaminated by the mercury emission lines from streetlights. Site surveys by Walker (1970, 1973), in California and Arizona led to results which are now well known; although other criteria for a useful site (minimal air turbulence, high percentage of clear nights, etc.) could also be applied, over half of southern California was found to be unsuitable for future faint-object work on the basis of sky brightness alone. Two thirds of the major observatories in Arizona were in a "borderline" condition.

Because of the unexpectedly rapid growth of Tucson and Phoenix in the 1960's, astronomers at the Kitt Peak National Observatory also began programs to measure and monitor the sky brightness. During 1971-1972, the population of Tucson grew by 4-5% per year while the sky over Tucson brightened by 10-15% per year (Hoag, Schoening, and Coucke 1973). In June, 1972, thanks to lobbying efforts by local astronomers and cooperation among city officials, astronomers, and lighting engineers, Tucson passed an ordinance restricting the placement and emissions of new luminaires in the city (Hoag 1972). Follow-up measurements of the city's sky brightness (Hoag 1976) showed that the growth of further pollution had been largely arrested. Tucson passed a second, tougher lighting ordinance in 1982, and a program to get similar legislation adopted in other cities and counties of southern Arizona has met with considerable success (see, e.g., Thomsen 1982).

Some other significant studies that may be mentioned here are the scanner observations of the night sky spectrum around the Palomar and Mount Wilson Observatories by Turnrose (1974) and similar work for the sky near Lick Observatory by Osterbrock, Walker, and Koski (1976). Both the Lick and Palomar Observatories have pursued active programs to control the growth of "spectrally dirty" lighting in their areas (Faber and Reed 1980, 1983; Steinberg 1983 and Thomsen 1984). In Canada, a large-scale study of the light pollution across Ontario province was conducted by the Royal Astronomical Society of Canada between 1974 and 1975; the primary measurements were done with "null-type" visual photometers (Berry 1976). The mathematical model of sky brightness used to incorporate the results of the study will be discussed in Part IV.

III. Measuring Sky Brightness

(a) General Requirements. To do useful photoelectric photometry of the night sky, with fixed or portable photometer systems, requires only a few basic items of hardware and a few simple (but carefully followed) observational techniques. Some specific observing projects are discussed in sections (d) and (e).

The observational hardware can be divided into four main systems: an imaging system (telescope or telephoto lens), a detection system (diaphragms to control how much sky is examined, filters to control the spectral region sampled, a photosensitive device (usually, a photomultiplier tube), and the associated electronics), a system to provide physical support and tracking for the equipment, and some instrumentation to display various kinds of related information that will be helpful in interpreting the photometry. The last category ought to include a thermometer, a device to measure altitude and azimuth or hour angle and declination, and a standard time (UT) clock; two other useful items would be a sling psychrometer (to measure relative humidity) and a barometer.

Any photoelectric system that is set up for stellar photometry can be used to measure sky brightness. In fact, sky brightness measures are normally taken every time the magnitudes and color indices of stars are obtained. Rather than simply subtracting the sky's contribution and forgetting about it, however, an observer will now want to systematically observe it and calibrate the measurements in terms of the perceived brightnesses of standard stars.

It will be assumed that observations are made in the UBV system, on clear nights when the Moon is not visible. Some interesting projects could be designed around other filter systems, but use of the UBV system allows for direct comparison of one's results with previous visual and photoelectric photometry and also makes available a large number of standard stars.

To be able to use stars as "calibration sources", an observer must know how to transform observed magnitudes and colors of stars to their standard system values (as given in catalogs). This means being able to correct nightly observations for the attenuating effects of Earth's atmosphere (extinction) and (having done that) to convert the "above atmosphere" instrumental magnitudes and colors to their standard values.

Such transformation coefficients, as the latter are called, will generally be known as a result of many night of stellar observing, as the observer gains a working knowledge of the system. Ideally, the "above atmosphere" values will only differ from the standard values by a constant amount, but it is more likely that they will follow relations of the form

$$V = C*v_o + D \qquad (1)$$

$$(B-V) = E*(b-v)_o + F \qquad (2)$$

(similarly for (U-B)), where v_o and $(b-v)_o$ are the observed but extinction-corrected magnitudes and colors. The transformation slopes (C and E) will probably be near 1.000 but not exactly equal to it; the deviations from unity can often be traced to slight differences among the average wavelengths of the observer's filters and those of the standard system.

In general, the atmosphere's effects upon starlight will NOT remain the same from night to night. They may even change from one part of a night to another, or from one side of the meridian to the other. Some detailed treatments of extinction may be found in Hardie (1962), Hall and Genet (1982), and Henden and Kaitchuck (1982). For most of the work being discussed here, however, it will probably only be necessary to determine the basic, large-scale extinction properties of the atmosphere on any given night. All that is really needed is to pin down the "zero point" of the photometry equipment: as seen through a particular filter, to what brightness does a certain number of counts correspond?

In the UBV system, an extinction coefficient is often expressed as

$$K = k' - k''*(b-v) + k''*X \qquad (3)$$

where k' is a constant and X is the air mass. The second term above is a part of the extinction that changes as a star's perceived color changes (as it rises or sets); it is generally small relative to the first term. The third term is a part of the extinction that changes with air mass; it could be visualized as being due to a change in the scattering properties of the air as the horizon is approached. Again, this term's contribution is usually small compared to the first term's. One observes stars of a variety of intrinsic colors and magnitudes, over a range of air masses, to determine the relative importance of the terms on each night. A knowledge of which terms are small enough to generally be neglected will develop over many nights of using the system.

It may be possible to bypass the necessity of explicitly determining nightly extinction when a good "feel" for the stability of the observational hardware has been obtained. If it can be shown that the photometry system yields the same counts vs. magnitude calibration night after night, if the photometer voltage can be reset exactly night after night, and if it is apparent that neither the electronics nor the filter transmission curves are significantly "aging", one may be justified in only observing a few standard stars each night. This procedure strikes the author as rather risky, but it may be justifiable when time constraints are important in making the observations (e.g., the weather is known to be slowly changing, the Moon is due to rise soon, and the like). Whether to make explicit extinction determinations each night or to rely upon the system stability and a general calibration is left to the discretion of each observer. A "hybrid" approach, using one or the other technique when it seems appropriate, may be the best compromise between speed and accuracy. In any case, however, the estimated uncertainty of a single observation should be quoted.

(b) Units of Brightness. What a telescope receives from point sources (which stars approximate) is the quantity called FLUX: the flow of energy per second onto each square centimeter of detector surface. If an extended radiation source (such as a patch of sky) is observed, the direction from which one views the source must be considered; it is necessary to speak of INTENSITY, the flux directed into a certain angle of view. For a star, the deflection or counts will be directly proportional to the received flux; for an extended source, the deflection or counts can also be considered as proportional to a flux once the angular area of sky included in the photometer aperture has been considered.

A common unit of brightness for extended sources is the "magnitude per square arc-second". One arc-second is 1/3600 of a degree, and one square arc-second is the area of a square patch of sky whose sides are arcs subtending one arc-second of angle each. (Since most photometer systems use round, not square, diaphragms, the equivalent circular patch of sky will have an angular diameter of C.564 arc-second.) The mag./(")^2, as it is abbreviated, is a number equating the brightness of the patch of sky to that of a point source like a star. For example, if the sky's brightness in some direction were $18^{m}.8$/(")^2, a patch of sky one square arc-second in area would be as bright as an 18.8-magnitude star seen against black space.

Another common brightness unit is the "magnitude per square degree", abbreviated mag./(°)^2. Since one degree is 3600 arc-seconds, one square degree will be (3600)^2 square arc-seconds, or 12,960,000 (")^2. One square degree of sky will, thus, be 12,960,000 times brighter than one square arc-second of sky; expressed in magnitude form, this is 17.78 magnitudes lower in number than the mag./(")^2, or

$$\text{mag.}/(^{\circ})^2 = \text{mag.}/('')^2 - 17^{m}.78 \ . \qquad (4)$$

A less familiar, but perhaps more useful, brightness unit is the "S10 unit": the number of 10th-magnitude stars needed to match the brightness of one square degree of sky. For this discussion, S10 units will be used for visual (V) observations only (most of the qualitative descriptions of night sky brightness are based upon visual observations). Unlike mag./(°)^2 and mag./(")^2, S10 units are directly (not logarithmically) proportional to the sky brightness: double the brightness and the S10 units also double, since twice as many "light sources" will be needed. The brightness of one square degree of sky that could be matched by one 10th-magnitude star would be $10^{m}.0$/(°)^2; this would also correspond to one S10 unit. A sky 100 times brighter (100 S10 units) would be five magnitudes brighter (lower in number) per square degree, or $5^{m}.0$/(°)^2 . Following the above argument, it is not hard to show that the three brightness units are related by

$$-2.5*\log(\text{S10}) = \text{mag.}/(^{\circ})^2 - 10^{m}.00 \qquad (5)$$

$$-2.5*\log(\text{S10}) = \text{mag.}/('')^2 - 27^{m}.78 \qquad (6)$$

Other, less familiar units are sometimes seen in the literature. Units of energy per second per square centimeter per solid angle are generally known as units of "luminance". The most common of these are the "stilb" (lumens/solid angle/cm^2) and the "lambert" ($1/\pi$ times the number of stilbs). These and related units will not be used further here; interested readers are referred to Table II of Berry (1976) for some equivalences.

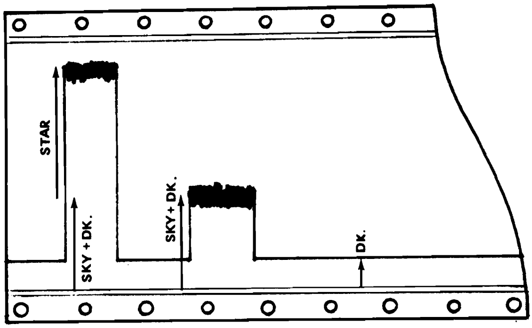
The brightness of an unpolluted sky, illuminated only by airglow, has been estimated by various researchers (including some of those mentioned in Part II) as being about $22^m\!.0/('')^2$ (equivalent to $4^m\!.2/(^\circ)^2$ or 200 S10 units). The densest star clouds of the Milky Way may add another hundred S10 units to this "natural" brightness level (in spots). Table 2, adapted from Berry (1976), displays some equivalent values of the brightness units, and some qualitative descriptions, for skies with different degrees of light pollution. (A revised form of this scale may be found in Berry (1977).)

Table 2 Visual Levels of Sky Brightness

S10 Units	Mag./$('')^2$	Mag./$(^\circ)^2$	Description
250	21.7	4.0	The "natural" level of sky brightness. The sky is crowded with stars, and the Milky Way extends to the horizon. Clouds appear as black silhouettes.
270	21.6	3.9	Same as above, but glows on the horizon from distant cities are visible.
350	21.4	3.6	The Milky Way cannot be seen near the horizon, though it is bright overhead. Clouds near the zenith appear grayish. Clouds near city glows appear bright.
750	20.6	2.8	Subtle details of structure in the Milky Way are lost, even though the Milky Way is still prominent. The faintest naked-eye stars are no longer detectable. Clouds are bright near the zenith.
2250	19.4	1.6	The Milky Way is marginally visible, only near the zenith. The sky looks dull gray except along the horizon in the directions of cities; there it is bright and discolored.
5000^+	18.5	0.7	The sky is bright and discolored everywhere. Only a few hundred stars are visible.
20000^+	17.0	-0.8	Only the very brightest stars are visible. The sky's overall color is becoming apparent.

(c) Obtaining and Reducing the Observations (An Example). Figure 2 illustrates the general procedure for taking stellar photometry, which can also be applied to the specific observations needed for night-sky photometry. A star is centered in a diaphragm of some physical (linear) diameter D (say, in millimeters), and readings are taken of a "signal" (anode current or pulses) over some time period (10 seconds is typical).

The "signal" will actually involve contributions from starlight, the light of the sky let in by the diaphragm, and a system "noise" called dark current. After the "signal" has been measured, the star is moved out of the diaphragm manually (with the telescope slow motion controls) and a reading of "sky" (actually sky plus dark current) is taken. The "sky" reading is subtracted from the "signal" to give a reading which is due to the star's light only. If the dark current is especially strong or shows evidence of variability, it can also be explicitly measured by using a dark slide, prism, or mirror to block off the photomultiplier cathode from incoming light and then sampling the "no light" output.



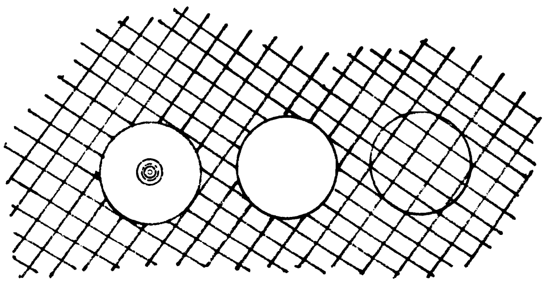


Figure 2 — Procedure for stellar photometry. Readings (in this case, deflections on a chart recorder) are taken for a star centered in the photometer diaphragm, then for an adjacent star-free field, and finally for "dark current" (thermal noise of the photocathode).

Sky brightness photometry is done in a similar way. Standard stars are observed and the effects of the sky near them subtracted. Dark current readings can then be subtracted from the "sky" readings to yield a net brightness value for that part of the sky. But, similar readings can be taken (in some systematic way) for OTHER areas of sky as well, and their net brightnesses can be compared to the brightnesses of the standard stars. If the telescope or telephoto lens focal length is known, the linear diameter D of the diaphragm used can be converted into an angular diameter, and the angular area of the patch of sky that the diaphragm includes can be calculated. With this quantity known, the net sky brightness readings can be expressed in "magnitude per unit area" or "S10 unit" form.

Suppose one observes a star, then a patch of sky, through a diaphragm which includes an area of sky of A $('')^2$. The net star reading ("signal" minus adjacent "sky") is directly proportional to the received flux F_*, and F_* will always be taken to represent the deflection or counts due to the star alone. The net sky reading could be for the sky adjacent to a standard star, or it might be for some other patch of sky (one probably brighter or fainter than the one near the standard star). Regardless of where the sky patch being considered is, let us call the deflection or counts for it F_s. Assuming the same sample times for star and sky, and using the definition of magnitude differences, leads to the following relation:

$$m_s = m_* + 2.5*\log(F_*/F_s) \qquad (7)$$

How is this relation interpreted? F_* and F_s are observables: quantities measured directly at the telescope. m_* is the apparent magnitude of the standard star as seen at the bottom of the atmosphere; if the transformation slopes discussed in section (a) are nearly 1.000, m_* will be the standard-system magnitude (or color) of the star PLUS the amount of extinction contributed by the atmosphere. m_s, therefore, will essentially be the brightness of the patch of sky in the diaphragm expressed as a magnitude (or color) on the standard UBV system.

If the diaphragm of area A $('')^2$ lets through a certain amount of light, a diaphragm of one $('')^2$ will only pass 1/A as much. In magnitude units, the sky reading through the smaller diaphragm will be 2.5*log A magnitudes fainter (larger in number). Thus,

$$\text{mag.}/('')^2 = m_s + 2.5*\log A \qquad (8)$$

Using formulas (5) and (6) allows us to obtain results in the other brightness units:

$$\text{mag.}/(^\circ)^2 = m_s + 2.5*\log A - 17.78 \qquad (9)$$

$$\log(\text{S10}) = -0.4*m_s - \log A + 11.11 \qquad (10)$$

Given (see formula (1)) a transformation slope C and (formula (3)) an extinction coefficient K,

$$m_* = \frac{V}{C} + K*X \quad . \qquad (11)$$

Let us take, as an example, observations of the standard star HR 437 (Eta Piscium) and a patch of sky at +20° declination and hour angle 2^h00^m west. The V filter was used for observing the star, the adjoining area of sky, and the patch of sky mentioned above. The following information is also available:

Size of telescope: 12-inch, f/16 reflector
Photometer: S-11 tube (blue-sensitive), cooled with dry ice
Diameter of diaphragm: 1.4 mm
Latitude of observatory: +41°35'

Extinction coefficient
on this night: $K_v = k'_v = 0^m\!.35$/air mass

Transformation slope for V filter: C = 1.002

Coordinates (1985.0) for HR 437: RA = $1^h30^m40^s$ Dec. = +15°16'07"
Standard magnitude, color: V = 3.62 B-V = 0.97

Hour angle of observation of HR 437: $HA_* = 1^h44^m$ west

Ten second sample times were used. Counts have been corrected for tube dead time.

"Signal" (star+sky+dark)	=	235654	
"Sky" (sky+dark)	=	1764	(This is the sky adjacent to the star field, not the "patch" at 2^h00^m west, +20° Dec.)
Dark current	=	36	
Counts for the "sky patch"	=	1953	

The net star counts are $F_* = 235654 - 1764 = 233890$.

The net counts for the "sky patch" are $F_s = 1953 - 36 = 1917$. We could also have computed F_s for the sky adjacent to the star.

To allow for extinction in the V magnitude of Eta Psc, the airmass at which it was observed must be evaluated. For zenith angles less than about 60°, the airmass X is essentially equal to sec Z, and

$$\sec Z = 1/(\sin L*\sin(Dec) + \cos L*\cos(Dec)*\cos(HA)) \qquad (12)$$

where L is the latitude of the observatory and L, Dec, and HA are all in degrees. In this case, L = 41.5833°, Dec = 15.2686°, and HA = 26.0000°, yielding X = sec Z = 1.283 . Then

$$m_* = \frac{3.62}{1.002} + 0.35*(1.283) = 4.06$$

and $m_s = 4.06 + 2.5*\log(233890/1917) = 9.28$. This is the magnitude of the "sky patch", as seen through the diaphragm, on the standard UBV system.

To express this result in "magnitude per unit area" form, one must now calculate the area of sky included by the diaphragm. For a telescope or telephoto lens of focal length F millimeters, the scale is

$$s\ (''/\text{mm}) = 206265''/F\ (\text{mm}) \quad . \qquad (13)$$

A 12-inch, f/16 telescope has F = 12*16*25.4 mm or 4880 mm. The scale is s = 206265"/4880 mm = 42.3"/mm. A diaphragm of diameter D = 1.4 mm will then correspond to an angular diameter d = 1.4 mm * 42.3"/mm or 59.2 arc-seconds on the sky. For a circle of diameter d, the area (in linear or angular units) will be $\pi*(d/2)^2$; in this case,

$$A = \pi * (59''.2/2)^2 = 2750\ ('')^2 \quad .$$

Finally, $\text{mag.}/('')^2 = 9.28 + 2.5*\log(2750) = 17.88$ and, by use of formula (10), log(S10) = 3.96 and S10 = 9120 units (a quite light-polluted sky).

It is assumed that, when the observations were made, the observer also recorded the temperature, time of night, weather conditions, and any other pertinent information.

(d) Projects for Fixed Photometers. Observers with photometers attached to permanently mounted telescopes can obtain some useful information about light pollution in general and some data which may help them plan their own future observations at the site. Questions that can be addressed by repeated, systematic observations at one site are:

(1) How does the sky's brightness in a given direction (at the zenith, say, or above a particular city glow) change on the short term? How much does it depend upon humidity, snow cover, time of night, and other factors? Little exact information is available. Observers at dark sites (e.g., Kalinowski, Roosen, and Brandt 1975) have noticed variations that could probably be traceable to changes in the airglow, but much less is known about the brightness fluctuations of light-polluted skies. To be able to convincingly show a long-term change in the light pollution, one must have a good sense of how great the short-term variations are. In a sense, one is evaluating the "noise level" imposed upon the illumination by changing atmospheric conditions.

Occasionally, an "episodic influence" (such as the dust from a volcanic eruption) will change the scattering properties of the atmosphere (see, e.g., Heidel 1972). Under these circumstances, systematic observations of sky brightness and stellar extinction over many nights could also be of interest as an environmental study.

(2) Is the sky's overall brightness changing with time? To evaluate lighting trends will require photometry over many months or years, although the numbers of nights per month or per year do not have to be excessive. The short-term "noise" in the measure-

ments, due to changing weather conditions, ought to be pretty well known. One might choose, as did Hoag, Schoening, and Coucke (1973), to examine the sky brightness directly above one of the horizon glows from an urban center rather than the brightness at the zenith; changes in the illumination from one light source may be better correlated to changes in the population or lighting policy of that one center than will changes in the zenith brightness (which is the sum of contributions from several urban centers). A little detective work — obtaining recent population figures, researching the lighting plans for nearby towns, counting streetlights and sorting them by types and wattages, and keeping an eye open for changes in the lighting policies — will provide some additional data for interpreting your observations.

(3) Is the type of lighting in the area changing with time? What effects does this have on the brightness or "spectral dirtiness" of the night sky? Multi-band photometry can yield some information on the relative importance of different lighting types in an area, since each common type of lamp displays its own characteristic emission pattern (Figure 1). Mercury and multi-vapor lamps emit much of their energy between 3500 and 5000 Angstroms (in the U and B filter bandpasses), while high-pressure sodium lamps have important emission beyond 5000 Angstroms (in the V filter bandpass). One can compare UBV results with numbers of streetlights of different types in nearby towns. Narrow-band photometry and spectrography will, of course, provide more exact information; but even broadband photometry will still be useful because of the lack of any such information in most areas.

Whatever the ultimate goal of the observations, the most useful results will come from photometry repeated in a systematic fashion night after night. Figure 3 shows an observational "net" which will be most useful for a photometer on an equatorially-mounted telescope. It consists of observations taken along strips of constant declination, at a spacing in hour angle that is adjusted to match the perceived change in brightness across different parts of the sky. Near the horizon, and particularly near glows from towns, the spacing is less than near the zenith. For fairly dark sites, it will be useful to note the position of the Milky Way; it will show up in the data as higher-than-normal readings forming a band that cuts through the observational net. For sites where the zenith brightness approaches 2000 S10 units, the Milky Way's influence will hardly be detectable.

If the observer has time constraints (personal or related to the weather), a smaller "net" can be used. One can make measurements at different altitudes (say, at 15^{o}, 30^{o}, 45^{o}, 60^{o}, and overhead) along the four cardinal directions, or along directions symmetric about the strongest horizon glow from a town. The conversions from a given altitude and azimuth to the appropriate hour angle and Dec. to be set at the telescope are

$$\sin(\mathrm{Dec}) = \sin(\mathrm{alt})*\sin L + \cos(\mathrm{alt})*\cos L*\cos(\mathrm{az}) \quad (14)$$

$$\cos(\mathrm{HA}) = (\sin(\mathrm{alt}) - \sin L*\sin(\mathrm{Dec}))/(\cos L*\cos(\mathrm{Dec})) \quad (15)$$

where the altitude, azimuth, latitude, and HA, Dec are all in degrees. For example, at latitude 40° north, an azimuth of 225° (southwest) and an altitude of 45° would be viewed by a telescope set to HA = $2^h00^m20^s$ west and Dec = +4°06′. One can generate a table of such values for the particular observatory latitude and use them night after night.

It may be noted from Figure 3 that an equatorially-mounted telescope cannot easily access the sky below the north celestial pole (or the SCP, for southern hemisphere observers). This area can be observed with a portable photoelectric photometer or studied photographically. It may be especially important to do this if there are strong glows from towns near the northern horizon.

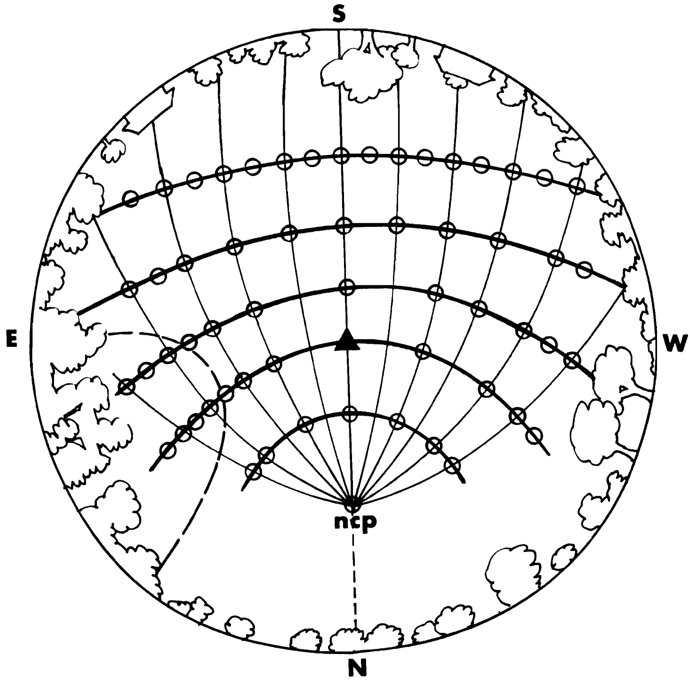


Figure 3 — An observational "net" for a fixed, equatorially-mounted telescope. The view is a "fish-eye" view from above the observatory (located under the filled triangle, and for which the filled triangle would be the zenith direction). The north celestial pole is designated by "ncp", and the curves opening southward from it are circles of hour angle. Each such arc represents positions 1 hour east or west of adjacent arcs. The east-west curves are curves of constant declination, in this case (for latitude 40° north) -20°, 0°, +20°, +40°, and +60°. The dashed curve opening out to the north of east is the perceived boundary of the horizon glow from a nearby town; observations in the "net" are more closely spaced here.

(e) Projects for a Portable Photometer. Observers with portable photometers can make significant contributions to the study of how light pollution affects different geographic regions. With the model to be discussed in Part IV, they can also investigate some details of how the atmosphere in a region scatters and absorbs the light from towns. Particular questions that can be addressed are:

(1) How does the brightness of the sky directly above an urban center depend upon its population? Is the number of luminaires directly proportional to the number of residents? It seems reasonable to think that such a proportionality exists. Cases where a simple relationship does not exist can also be demonstrated (abnormally high or low amounts of lighting because of poverty, mountainous terrain, military or industrial activity, etc.). It is not surprising, given the factors that may enter such considerations, that different investigators have found different dependences of a town's light output upon its population. Walker (1977) found that the total light output of cities in California went roughly as $P^{0.8}$, while Pike and Berry (1978) found that the downtown zenith brightnesses of cities in Ontario province went roughly as $P^{0.5}$ (the B_z values were assumed proportional to total light output except for the largest cities, where distant sections would not contribute as much light as the relation would predict for a "point source" of lighting). Explicit evaluation of the exponent in the population dependence for one's area will probably give a value unique to that area, and a knowledge of that particular value will enable one to estimate how the light pollution will change as the population of nearby towns changes.

(2) How does B_z change with distance from an urban center? What is the "circle of influence" of a city's lighting, beyond which the sky is still at a (specified) low level of brightness? The form of the falloff of B_z with distance, called the "Q function" (see Part IV), may be expected to depend upon the viewing geometry and the atmosphere's scattering and attenuating properties. The value of B_z in a given location will actually be due to contributions from various lighting centers, and the effects of each will have to be carefully evaluated by some specific procedures. Again, the "Q function" will probably be unique for a specific geographic region.

(3) How does B_z in a given location depend upon altitude? Observers in mountainous areas (or people who can afford to rent airplanes and carry photometers up in them) can provide information on the locations and thicknesses (scale heights) of aerosol layers in the troposphere.

A number of the investigators mentioned earlier (Walker, Berry, Hoag) describe simple portable photometer systems. Some of the low-cost systems now being marketed can also be adapted to field use. Whatever the system used, the projects should be carefully defined. Sites where observations will be taken can be found from street and topographic maps of an area, followed perhaps by a drive to those areas in daylight to locate possible shortcomings (e.g., swampy ground, "no trespassing" signs, etc.). When the observations are made, carefully note location, weather conditions, and anything else that may be of future use in interpreting the observations. The items above all deal with measuring zenith brightness, but other sky positions may also be of interest to observe; for example, Walker (1977) measured the sky brightness at an altitude of 45^{o} in the direction of an urban center and that of a point at the same altitude in the opposite direction.

IV. Modelling Light Pollution

(a) The Scattering and Absorption of Light. All the observations one makes of the sky's brightness in different directions contain information, not only about the light outputs of nearby towns but also about how the local atmosphere affects the passage of light through it. A proper treatment of radiative transfer in a stratified planetary atmosphere is beyond the scope of this article, but some basic properties can be outlined. The numerical model described in section (b) below can still be of great use in describing the form and growth of light pollution in an area, even though it is necessarily an approximation of reality.

Light travelling through an atmosphere can be "scattered" or "absorbed". A scattering is an event that changes the direction (and, sometimes, the wavelength) of a photon (the second effect mentioned will not be considered further here). The event may be an encounter with a dust grain, a colloidal particle, or an atom/molecule of gas. The encounter may involve actual excitation/de-excitation of an atom, or it may be a "refraction" of the photon by close-range interaction with an electrical field on the surface of the dust grain or colloid. With the exception of "airglow", refraction will be more important for the large-scale effects being considered here.

The atmosphere can also absorb photons. Absorption, in this context, is not merely a scattering of photons out of one particular direction: it is their conversion to other forms of energy. Photons may be absorbed and converted to kinetic energy (increasing the motions of atmospheric particles), or they may be used to dissociate molecules, or they may be used to provide internal motions (heating) to particles. Such photons are permanently lost from the light path, whereas photons that were merely scattered out of their original path have some small chance of being scattered back into it.

Materials that efficiently scatter photons into directions near their original paths are called "forward scattering" materials; those that scatter photons efficiently in the reverse directions are "back scattering". Some of the fine particles in Saturn's rings, seen backlit by the Voyager probes, were very bright (strongly forward scattering). The rayed craters on the Moon (e.g., Tycho and Copernicus) are brightest at the Moon's full phase; they strongly back scatter the sunlight. Anyone who has tried to drive through a dense ground fog at night with high beam headlights on knows how strong its back scattering can be! Aerosols often partake of both extremes, being strongly forward scattering, mildly back scattering, and doing little scattering at right angles to the light path; there is a strong glow on the horizon at night in the direction of an urban center (direct and forward-scattered light) but often also a glow on the horizon opposite the urban center (back-scattered light).

(b) The "Single Scattering" Model. Bertiau, de Graeve, and Treanor (1973) proposed a physical model for light propagation through an atmosphere which should prove very useful for describing the form and growth of light pollution. In their model, a point on the sky directly above any observer is illuminated in only two ways: by light reaching the point directly from nearby light centers, or by light which has been scattered into that direction by a single (one-time) encounter with an atmospheric particle. Multiple scatterings are not allowed, which will make the model less applicable to conditions when haze or fog is present but which simplifies the mathematical treatment.

Photons from a given light center will either travel directly toward the overhead point or be forward-scattered toward it (see Figure 4); the scattering involves a deviation of no more than some angle ϕ (characteristic of the scattering material) from the scattered photon's original path. The "overhead point" that is measured will actually be some concentration (layer) of aerosols that can efficiently back-scatter some of the light reaching it down to the observer.

If multiple scattering can be ignored, it is not hard to show that the photons reaching the overhead point from a particular light center (town) can only be those within a spindle-shaped region between the overhead point and the light center; the spindle's shape depends upon ϕ. The total overhead brightness will be the simple sum of contributions from the "spindles" of the surrounding light centers.

The light along each path within a "spindle" will be attenuated by true absorption by the atmosphere. If X is the distance from a town to the overhead point (aerosol layer), and the layer is some height h above the ground, all the light reaching that point will have been dimmed by roughly a factor

$$e^{-k*X} = e^{-(D^2 + h^2)^{\frac{1}{2}}}$$

where D is the ground distance between the observer and the light center. The attenuation between the overhead point and the observer (e^{-k*h}) is considered negligible.

The numbers of photons received at any particular point will decrease with the square of the distance from their source; this is just the "inverse square law" which describes energy spread over the surfaces of larger and larger imaginary spheres. For light directly travelling to the overhead point from a town, the distance involved is X. For scattered light, the numbers of photons will diminish until the point from which they are scattered (anywhere within the spindle) is reached; then that point will act as a "new source" of photons, whose numbers will fall off as the square of the distance of the scattering point from the overhead point. For a given town, such scattering points will occur throughout the "spindle", so an integration along its length is necessary. The result is that singly-scattered light, to a first approximation, acts like direct light whose brightness is only diminished as X, not X^2.

The "Q function" is defined as the sum of intensities of direct and scattered light, received at the overhead point, relative to the initial

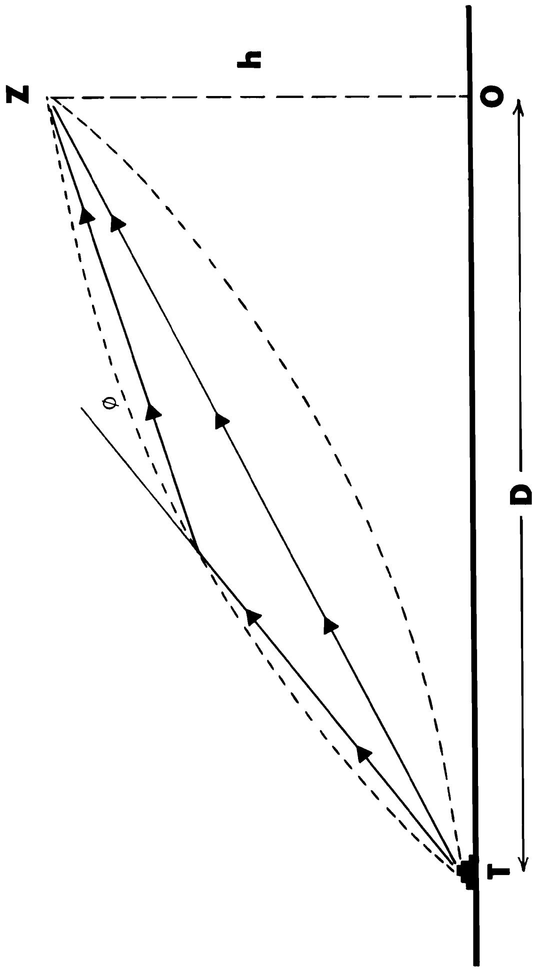


Figure 4 — The "single scattering" model of light pollution. The observer, at point O, looks upward to a back-scattering aerosol layer at point Z. Light reaching Z from the town, T, can only reach Z from points within the "spindle" indicated by the dashed arcs; the exact shape of the spindle is determined by the scattering angle ϕ which characterizes the aerosol.

intensity of light from the town. It is given by

$$Q(D) = \left(\frac{U}{D^2 + h^2} + \frac{V}{(D^2 + h^2)^{\frac{1}{2}}} \right) e^{-k*(D^2 + h^2)^{\frac{1}{2}}} . \qquad (16)$$

The zenith brightness at any location a distance D from <u>one</u> town will be

$$B_z(D) = a*P^n*Q(D) \qquad \text{(S10 units)} \qquad (17)$$

where n is the exponent of the brightness dependence on population (discussed in section (e) of Part III) and a is a constant of proportionality which will incorporate the fraction of the light reaching the overhead point which is scattered downward to the observer. In general, if there are several towns (at distances D_1, D_2,...) contributing, the total overhead brightness will be

$$B_z(\text{total}) = a*P_1{}^n*Q(D_1) + a*P_2{}^n*Q(D_2) + \ldots \qquad (18)$$

Modelling the light pollution for an area, then, involves determining the constants a, n, U, V, h, and k.

<u>(c) Determining the Constants</u>. Since, in general, the sky brightness at a given location will be due to the contributions from several light sources, it will be best to try to evaluate the constants for a town which is as separated as possible from others in the geographic region. One can also make use of the fact that different parts of the "Q function" will be of greatest importance at different distances from the center of a town.

For towns which are not too extended (not too different from "point sources"), n can be determined by the procedures discussed in section (e) of Part III.

Within 10-20 km of such a town, scattering and attenuation of the light will be minimal; the Q function will look a lot like $U/(D^2 + h^2)$ (see Figure 5). At greater distances, D will be large in comparison with the height of the overhead point and the Q function will resemble $(V/(D^2 + h^2)^{\frac{1}{2}})e^{-k*(D^2 + h^2)^{\frac{1}{2}}}$.

Details of the fitting procedure are given by Pike (1976). The Ontario study found n = 0.5, a = 50, h = 2.4 km, U = 2.59 km^2, V = 0.08 km, and k = 0.026/km for B_z in S10 units.

<u>(d) Using the Model</u>. Once the constants for an area have been evaluated, the model can be used with available population figures to determine the best remaining observing sites. It can also be used with projections of population growth to show the growth of the pollution. Pike and Berry (1978) have presented the results of such an analysis for Ontario province.

Figure 6 shows a "bubble graph" for a hypothetical region containing some large and small towns. The "bubbles" represent regions inside which the towns contribute 100 or more S10 units to the sky's

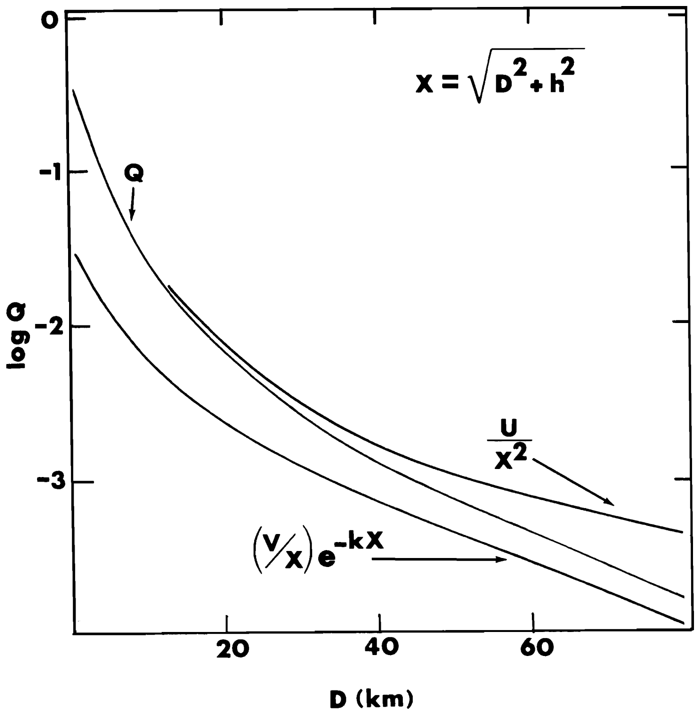


Figure 5 — The Q function and its approximations at different distances. Near towns which are not too spread out, the decline in brightness with distance is nearly the simple "inverse square law". At great distances, the effects of scattering and attenuation dominate.

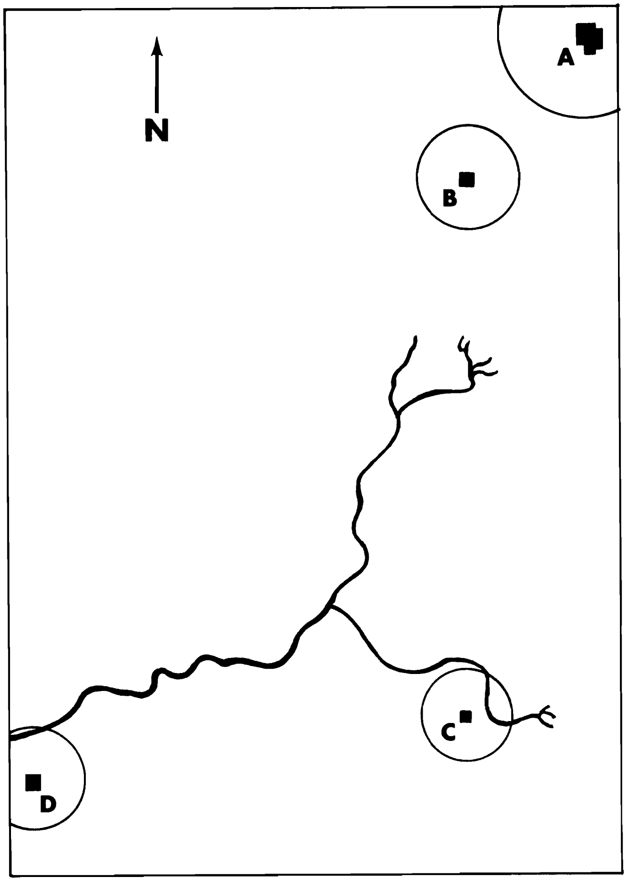


Figure 6 — An imaginary geographical region containing four moderate-sized towns. Town A has a population of 20,000, towns B and D both have populations of 5,000, and town C has a population of 3,000 people. The circles drawn around each town represent regions inside which each town contributes 100 or more S10 units to the sky brightness at the zenith.

brightness. Figure 7 shows an alternate way of displaying results: as numbers representing the sums of light contributions from the different towns for every 100-square-kilometer area of the region. In either case, the darkest remaining sites can be identified, and the gradual disappearance of those located between expanding "bubbles" can be studied. Table 3 lists the "bubble radii" for towns of different populations, as derived from the values found for the Ontario study.

Table 3 Distance from an Urban Center where Brightness Added = 100 S10 Units

Population	D (km)
10,000	11
50,000	17
100,000	20
250,000	24
1,000,000	33

V. Conclusions

Light pollution is a problem that concerns astronomers, conservationists, and anyone else who appreciates the disappearance of darkness and beauty. It is a problem for which photometry can provide some valuable knowledge. Many astronomical organizations would be very happy to receive new observational results, especially if they are obtained in a thorough, careful manner; among these are the International Astronomical Union, the American Astronomical Society, the Royal Astronomical Society of Canada, the Astronomical Society of the Pacific, the Astronomical League, and the International Amateur-Professional Photoelectric Photometry group. Whether the program is a small, short one or a long, ambitious one, it can be an important part of the work toward keeping the night sky dark.

1	2	3	5	9	18	31	65	186	3210
2	3	4	8	14	27	63	130	135	186
2	3	4	7	13	29	99	1618	123	65
2	3	4	5	10	18	54	99	57	36
2	2	3	4	7	14	18	29	22	18
2	2	3	4	5	8	11	14	14	9
2	3	3	3	5	5	8	9	9	6
3	3	3	3	4	5	7	8	6	6
5	5	4	4	5	6	10	10	10	6
10	9	6	5	7	12	13	18	13	11
23	13	11	9	10	13	37	62	37	12
88	46	14	10	11	18	62	1002	62	17
1601	89	25	13	12	14	37	62	36	12
88	47	22	13	9	12	13	17	12	10

Figure 7 — Use of the "single scattering" model to find the darkest sites in a geographical region. The region has been divided into squares 10 km on a side, and the brightness that each town contributes to any square is computed using the distance of the town from that square, the town's population, and the Q function. The number appearing in each square is the simple sum of the contributions from all the towns (in S10 units). Since the model is used to calculate the effects of light pollution, the "natural" sky level (200-250 S10 units) should be added to the value in each square to reproduce actual brightnesses observed at the telescope.

References

Berry, R.L. 1976, Journal of the Royal Astronomical Society of Canada, 70, 97.

---------- 1977, Astronomy, 5, No. 9 (September), 26.

Bertiau, F.C., S.J., de Graeve, E., S.J., and Treanor, P.J., S.J. 1973, Vatican Observatory Publications, 1, No.4 .

Faber, S.M. and Reed, S.M. 1980, Outdoor Lighting and Lick Observatory (summary report produced by the University of California at Santa Cruz, January 1980).

------------------------- 1983, Private-Sector Outdoor Lighting and Lick Observatory (summary report produced by the University of California at Santa Cruz, January 1983).

General Electric, Publication TP-109R (1975), High Intensity Discharge Lamps.

Hall, D.S. and Genet, R.M. 1982, Photoelectric Photometry of Variable Stars (published by IAPPP, printed by W.L. Myers, Minuteman Press).

Hardie, R.H. 1962, in Astronomical Techniques, edited by W.A. Hiltner (Chicago: University of Chicago Press), p. 178.

Heidel, K. 1972, Science, 177, 882.

Henden, A.A. and Kaitchuck, R.H. 1982, Astronomical Photometry (Van Nostrand Reinhold Co., New York and Cincinnati).

Hoag, A.A. 1972, Mercury, 1, 2.

--------- 1976, Publications of the Astronomical Society of the Pacific, 88, 207.

Hoag, A.A., Schoening, W.E. and Coucke, M. 1973, Publications of the Astronomical Society of the Pacific, 85, 503.

Kalinowski, J.K., Roosen, R.G. and Brandt, J.C. 1975, Publications of the Astronomical Society of the Pacific, 87, 869.

Norelco (North American Philips Lighting Corp.) 1972, Bulletin SOX-100.

Osterbrock, D.E., Walker, M.F. and Koski, A.T. 1976, Publications of the Astronomical Society of the Pacific, 88, 349.

Pike, R.C. 1976, Journal of the Royal Astronomical Society of Canada, 70, 116.

Pike, R.C. and Berry, R.L. 1978, Sky and Telescope, 55, No. 2 (February), 126.

Riegel, K.W. 1973, Science, 179, 1285.

Sperling, N. 1980, Sky and Telescope, 60, No. (July), 17.

Steinberg, S. 1983, Science News, 124, 58 (July 23).

Thomsen, D.E. 1982, Science News, 121, 269 (April 17).

------------ 1984, ibid., 125, 101 (February 18).

Turnrose, B.E. 1974, Publications of the Astronomical Society of the Pacific, 86,545.

Walker, M.F. 1970, Publications of the Astronomical Society of the Pacific, 82, 672.

----------- 1973, ibid., 85, 508.

----------- 1977, ibid., 89, 405.

5

COMPUTERIZED PHOTOMETRY FOR INTELLIGENT, EFFICIENT, AND FLEXIBLE OBSERVING

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I. INTRODUCTION

At the beginning of this century, the technology of big telescopes widened the gap between professional and amateur astronomy. Now another technological revolution, - microelectronics - may serve to bring amateurs and professionals closer together in their scientific activities. We believe that astronomical research will move away from the "mainframe only" mentality of large telescopes at the national centers, to a "cottage industry" typified by the effective use of smaller telescopes. The microcomputer will play a key role in this revolution.

For example, amateur astronomers with modest telescopes can carry out long-term photometric projects. Such ambitious critical work has two dulling drawbacks: data collection and data reduction. Data collection involves tedious and repetitious observations, while data reduction requires that atmospheric extinction corrections and transformations to a standard photometric system must be carried out on a large and accumulating mass of data.

To handle these chores in an efficient and intelligent way requires help. Today that aid can come from reasonably inexpensive microcomputers. We describe in this chapter how we tackled this task for the 61-cm telescope at the University of New Mexico's Capilla Peak Observatory. Although this is a professional installation, our procedures and solution apply to any telescope and automated photometer that can be interfaced to a microcomputer. Since we developed our system with inexpensive and readily available hardware, and developed the software in the popular BASIC language, others can duplicate our results without engineering assistance or the need to be a computer/electronics whiz. The end result is a system that is almost as flexible as the one at Kitt Peak.

Fig. 1. View toward southeast of Capilla Peak Observatory complex.

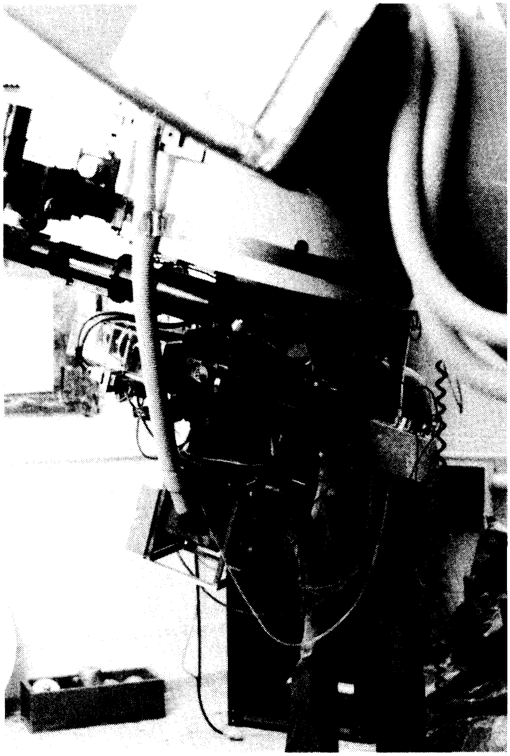

Fig. 2. Photometer and autoguider at the back end of the telescope. Gary Henson is at the eyepiece.

II. THE CAPILLA PEAK SYSTEM

Capilla Peak Observatory, located in the Manzano Mountains southeast of Albuquerque at an altitude of 2840 meters, offers an excellent site for photoelectric photometry. The Manzano Mountains block out the lights of Albuquerque, so the site is very dark. In fact, it is much darker than Kitt Peak (sky brightness of about 22.5 magnitudes per square arcsecond at V band on a moonless night). The weather is equivalent to that at Kitt Peak with 30 to 40 percent photometric nights. The main equipment is a Boller-Chivens 61-cm reflecting telescope with an f/13.5 Cassegrain focus, at which the photometer is located. This photon counting photometer, which uses a refrigerator cooled EMI 9658R photomultiplier tube, has a Kitt Peak-type filter slide containing UBVR and Hydrogen-alpha filters, whose position is controlled by a servo motor.

To conduct long-term photometric projects we modified the system to operate more flexibly so that a variety of programs could be carried out; more intelligently so the the observer could make realtime decisions at the telescope; and more easily so the post-reduction would be fast and efficient. We decided to run the photometer by a 48K Apple II+ microcomputer because it is relatively inexpensive, it has 8 slots on the mainboard for hardware expansion (much of which is available commercially), and strong software support. Apple also reveals the details of how their computer works, so it is easy to work out the interfacing to the real world. The data can go to both a printer (Epson MX-80) and a 5 1/4" magnetic disk (Microsci A40 drive with 40 track capability). An on-board clock (California Computer Systems Model #4724) keeps track of the time and data and provides system timing in Universal Time.

During an observation the computer commands the filter position and integration time. It logs a filter, time and counts; computes the mean counts per second and standard deviation from the mean at the end of the observation; and converts these to an instrumental magnitude with the corresponding statistical error. It also tags the observation with the air mass. Finally, all the pertinent information (source name, air mass, filter, etc.) are stored in a disk file for the night. This disk is taken down from the mountain and loaded in a twin Apple II+ (located in our departmental offices) for final reduction.

III. PHOTO

The heart of the system is a program called PHOTO, written in resident Applesoft BASIC. PHOTO interprets and executes simple commands and programs which control the photometer and reduce the data. The goal of this program is to make photometric observing simple, efficient, and intelligent. It is easily learned by a novice observer while at the telescope. PHOTO accepts three-letter commands. Any attempt (or accident!) to type in anything besides the valid commands results in a polite response by the computer asking you to try again. The commands are in mnemonic form. For example, FIL tells the computer to change the filter slide position (our filters are each given a code number for their slot position). The computer will them request the slot position. If the observer types "3", then the computer moves the filter slide to slot 3 where a V-filter is located. After the slide is positioned the computer waits for the next command. If at this stage the observer is lost, he/she can type HLP. This command loads in a "HELP" file that describes all of the commands accepted by the program. The observer may now type in INT, which does the integration routine. The computer asks for two numbers (separated by a comma): the number of integrations and the time (in seconds) for each. Typing "5, 10" for instance, will result in 5 integrations of 10 seconds each. The results will be displayed on the video screen and also be sent to the printer.

This procedure is PHOTO's "immediate mode" of operation. Commands are executed as they are entered at the terminal (see tables 1 and 2), but photometric observations typically run through a repetitive cycle of source and sky for a series of filters (such as UBVR). To command this operation in Immediate Mode is a waste of the observer's intelligence. Therefore, we designed PHOTO so that it allows the writing of short programs and their execution. PHOTO has a "Create Mode" to write programs and a "Run Mode" to execute them. The observer enters the create mode by typing CRE (Tables 2 and 3), then writing the steps of the program (Table 1). A typical program might contain the following series of commands:

PON (Connect the computer to the printer for output)
FIL-3 (Change the filter slide to slot 3; contains V filter)
INT-4,5 (Do 4 integrations for 5 seconds each)
FIL-4 (Change the filter slide to slot 4; contains B filter)
INT-5,5 (Do 5 integrations for 5 seconds each)
FIL-5 (Change filter slide to slot 5; contains U filter)
INT-6,5 (Do 6 integrations for 5 seconds each)
TIM (Update UT time)
STA (Print out name of object, RA, DEC, Hour Angle, Air Mass, Local Sidereal Time, Julian Date, UT date, and Orbital Phase)

This program can be developed in the Create Mode to allow looping (with a CON command to line 1, PON command), and a final END command to stop program execution. Once a program is written it is saved in a memory space called the Program Buffer (a buffer is a reserved space in the computer's memory). A RUN command then executes it.

The PHOTO program consists of two memory buffers and a main program. The two buffers are (1) the program buffer which stores a program, and (2) the data buffer which holds the data before it is saved on the magnetic disk. PHOTO has three operating modes within its main program. The first is the command mode which executes commands immediately. The second is the create mode which places programs in the program buffer without executing their instructions immedately. The third is the run mode, in which the instructions in the

TABLE I.

COMMANDS FOR THE IMMEDIATE OR CREATE MODES

APR	Change aperture size
DUM	Dump the data buffer to the disk
EXT	Exit the PHOTO program
FIL	Change the filter
HLP	Print a help-file explaining the commands
INT	Make Y integrations, each Z seconds long
LIS	List the program in the program buffer
OBJ	Select an object from the star list
PON	Enable the printer
POF	Disable the printer
SET	Set the real-time clock
STA	Print the status of the object
TIM	Update the time buffer

TABLE II.

COMMANDS FOR IMMEDIATE MODE ONLY

CRE	Enter the create mode
DEL	Delete a line from the program buffer
INS	Insert a line in the program buffer
LOD	Load a program from disk to the buffer
REP	Replace a line in the program buffer
RUN	Enter the run mode
SAV	Save the program in the buffer

TABLE III.

COMMANDS FOR CREATE MODE ONLY

CON Conditional branch to the line specified

END End of program. Also exit from run or create mode to immediate mode.

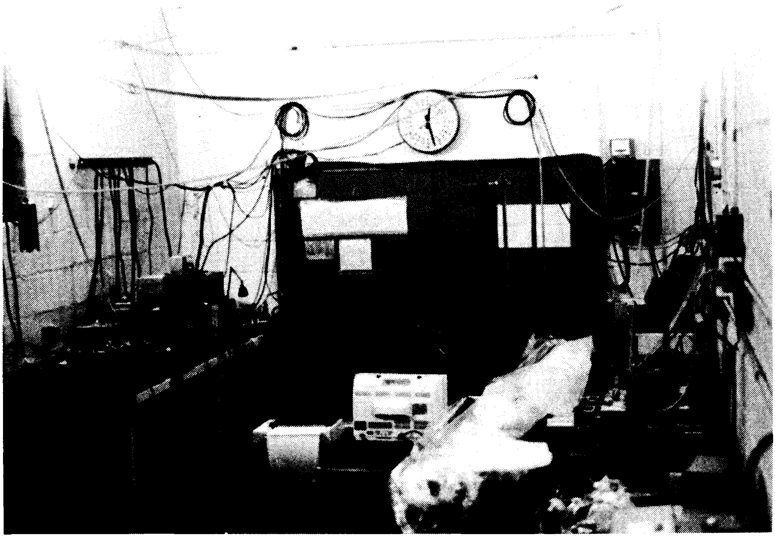

Fig. 3. Electronics room adjacent to the dome. Richard Elston is at the computer making an observation.

program buffer are executed in order.

The programming capability of PHOTO (modeled after the FORTH capability at KPNO) provides the observer with intelligent flexibility. For example, suppose the observing involves repeated UBV photometry of a binary star to a specified accuracy for each observation (we typically aim at 0.01 mag. or better). Having set the telescope on the star, the observer runs through the filters on the source (and then the sky) to find out the integration times appropriate for each filter which would provide the required accuracy. The observer then goes into the create mode make the program and save it in the program buffer. Then a RUN command automatically executes this program from the buffer. It can also be saved on disk as a text file and recalled at will. The programs are tailored for specific observational programs or each specific object, readily available to the user, and easily modified. This capability is particularly useful for long-term programs in which many objects are observed many times. Each object has its own program filed by the object's name.

We have rewritten PHOTO in a simulation mode to mimic its telescope actions on any Apple II+ in order to train novice observers so that time is not wasted on the mountain. The program functions exactly as it does at the telescope except that the filter, integration time, and counts must be typed on the keyboard. It can also be used to reduce any photometric data by hand, as long as it is in digital form.

Since the computer does a first-pass reduction of data, the observer can make real time decisions such as re-observing a variable if the errors are too large. The program will keep track of the orbital phases of binary stars and tell you what time to make the next obervation. The computer also handles the data bookkeeping, thus relieving the observer of this tedious task.

The data buffer contains space for 10 observations after which it automatically puts the buffer's contents on the disk appended to the file which is already present. We chose 10 as a compromise between writing to the disk after each observation (a slow process) or saving a large region of memory. Thus, in the case of a system crash we loose at most 10 observations, and usually less because the buffer dumps to the disk upon a crash. The lost data can be reproduced later from a printout.

Post reduction of the data is enormously simplified by having the data on disk. An editor program prints out the files and allows selective editing of bad entries. A reduction program measures the variable relative to comparison stars, subtracts out the sky background, and applies a heliocentric correction to the Julian Date. A transformation program uses observations of UBVRI standards to calculate the extinction for the night and the transformation coefficients to the standard UBVRI system. The reduced data is finally logged onto a library disk. For binary star systems, we can now easily determine the light curves. A plotting program (Scientific Plotter for Interactive Microwave) makes up and

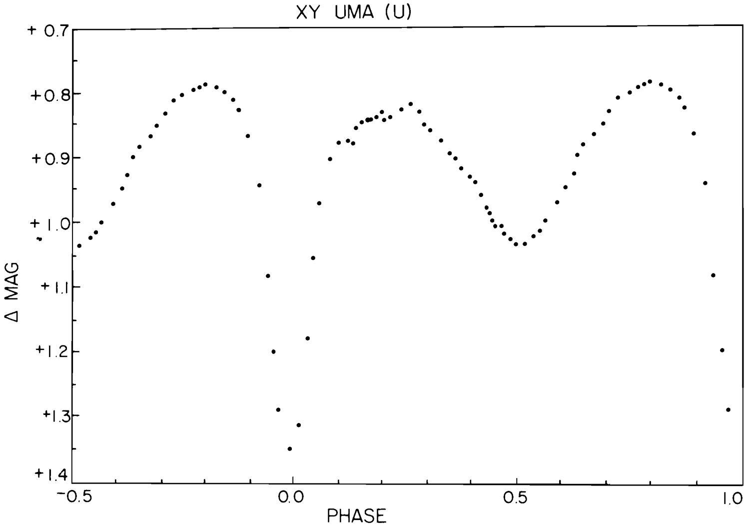

Fig. 4. U-band light curve of the RS CVn binary system XY UMa. Orbital period is 0.48 day. The complete light curve was done in two nights. Statistical errors are no larger than the size of the data points. Comparison star was +54 1278.

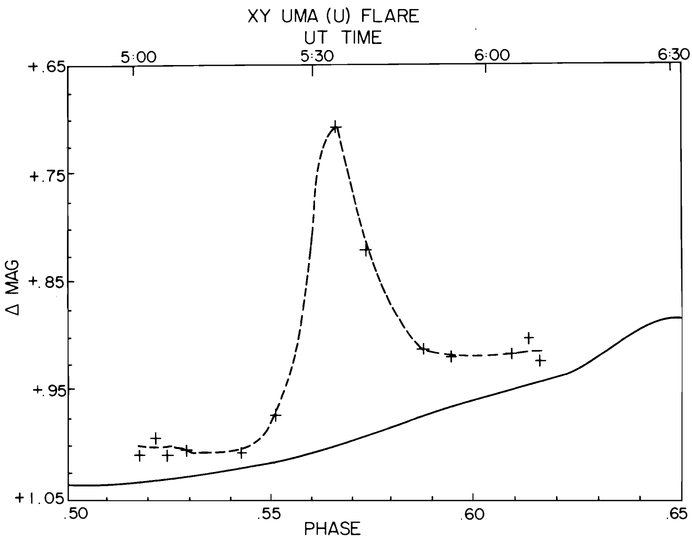

Fig. 5. Flare at U-Band from XY UMa on 31 January 1982. These data points have been removed from Figure 4. The "+'s" mark the actual data, the dashed line a Stineman fit to the points, and the solid line the underlying light of the system.

labels the graph of the raw data. We then use a smoothing, averaging, and curve fitting program (Curve Fitter, also from Interactive Microwave) to find the overall trends in the data. The graphical format permits quick evaluation of the data. We can reduce a night's data the following day and decide what observations are required during the next observing run.

One piece of advice from our experience: you will need to do plenty of data editing. A word-processing editor provides the simplest solution, but beware! Many of the commercial editors do not work with standard Apple text files, and most are rather expensive. We use APPLE PIE, an early version of PIE WRITER (now available from Hayden). We have found its global editing features are exactly what is required to easily edit the data files. A text editor is an essential piece of software for astronomical data reduction; and, of course, you can also use it to write your papers!

We are now adding a polarimeter to the system. The polarimetry program will be a subroutine of PHOTO. It will turn the polarizing element so many degrees and then keep track of the Stokes Parameters. We have also added 16K of memory to the system to accomodate the additional length of the program. When we are satisfied with it, we plan to burn the program into EPROMs with the disk version as backup.

IV. CONCLUSION

The computer, PHOTO, and the data reduction program make possible flexible, efficient, and intelligent observing. Since each photometric night is priceless (especially for historical records such as binary stars), the computer control of a photometer truly enhances the power of the observer. Over the past two years Capilla has become a very productive small telescope because of its computerized operation. During the next few years, the $2500 price of the computer system should drop by about a factor of two, thus opening the computer capability to people with limited budgets. It can bring a dedicated amateur's program up to the level of a professional observatory. Such increased capability will enhance the impact of amateurs for serious astronomical observations.

6

SMALL AUTOMATED PHOTOMETRIC TELESCOPES

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I. INTRODUCTION

In Volume I of this series of books on "Advances In Photoelectric Photometry", we (Boyd and Genet) discussed small automated photoelectric telescopes in terms of their history, astronomical considerations, and approaches to hardware and software. Attention was focused on small ground-based systems that were capable of observing a large number of medium-to-long-period variable stars every clear night. The various considerations involved were emphasized, rather than detailing a specific system. The Volume I chapter was written in May, 1983, and in November of 1983, an Automated Photoelectric Telescope (APT) of the type which had been described became fully operational at Fairborn Observatory West.

It is the intent of this second chapter (being written a year later in May, 1984) to describe the development and use of these systems at the Fairborn Observatory. We will also attempt to describe the current status of the development and use of APT's, and to suggest future directions that the development and applications of APT's might take. We apologize in advance for our somewhat narrow treatment of the topic. Not covered, for instance, are interesting developments in automated photoelectric telescopes used for short-period variables (continuous monitoring), or the intriguing automatic South Pole photoelectric telescope developed by the University of Florida to take asvantage of the unique South Pole geometry and long southern nights. We do expect that further papers on various automatic systems currently under development at other observatories will be appearing shortly, and we welcome the increased diversity of approach and enrichment of ideas that these new systems will bring to this field which is still it its infancy.

II. THE PAST YEAR: FINAL DEVELOPMENT AND OPERATION

The APT which one of us (Boyd) had been working on for four years finally achieved full automatic operation (including start-up and shutdown) in early November, 1983. The system is shown in Figure 1, and has already been described in some detail (references 1, 2, and 3). On its first night of operation, the APT collected a large amount of data which can be seen in Figure 2.

The initial APT observing program consisted of some 29 program stars, along with an equal number of comparison and check stars. Most of the program stars were variable stars, but a few were non-variable stars inserted to determine transformation coefficients. The observing program has been described elsewhere (Ref. 4), and the detailed data is available as an IAU Commission 27 File (Ref. 5).

On January 1, 1984, the APT observing program was expanded to 71 program stars. These stars consisted primarily of known variables of the RS CVn, Zeta Aurigae, and semiregular types, and a group of suspected RS CVn variables. The January through March 1984 APT observing program has been described (Ref. 6), and the data is available as an IAU Commission 27 file (Ref. 7). A number of papers have been (or are being) published on various results from the programs. Amoung these are papers on Epsilon Aurigae (Ref. 8), 5 Ceti (Ref. 9), and three semiregulars on the AAVSO Photoelectric Photometry Program (Ref. 10).

The use of APT's to discover new variable stars appears to be particularly appropriate. Discarding the results from stars found not to be variable is not quite as painful when the data was gathered automatically! In the first quarter of 1984, a number of new variable stars were discovered by the APT in Phoenix (Ref. 11 and 12). The use of APT's to discover new variable stars is being expanded, as will be described shortly, and such discoveries are clear indications of the usefulness of APT's.

APT's are also useful for monitoring a group of known variables for changes. Over a dozen known RS CVn variables have been observed by the APT in Phoenix, and the observations and light curves on these stars have been described and analyzed (Ref. 13). Besides Eps Aur, other Zeta Aur type very long-period eclipsing binaries are being monitored by the APT in Phoenix. This will give the first comprehensive photometric out-of-eclipse coverage of these interesting stars.

Shown in Figure 3 is a light curve of the semiregular variable star, Rho Per. This light curve was taken over a 150-day period from the APT at Fairborn Observatory West, and is typical of the work on semiregular variables. (Our thanks to the International Bulletin of Variable Stars, IBVS, for the use of this figure.)

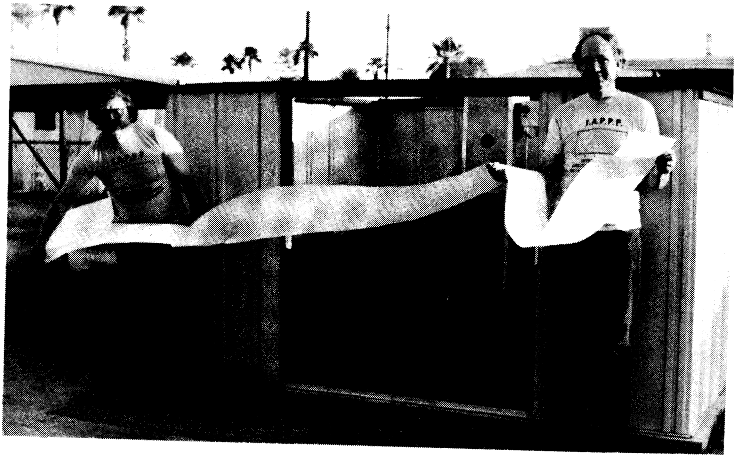

Fig. 1. The Automatic Photoelectric Telescope and its developer, Louis J. Boyd. It is located at Fairborn Observatory West in Phoenix, Arizona.

Fig. 2. Boyd (left) and Genet display the data taken on the first full night of totally automatic operation of the APT in Phoenix.

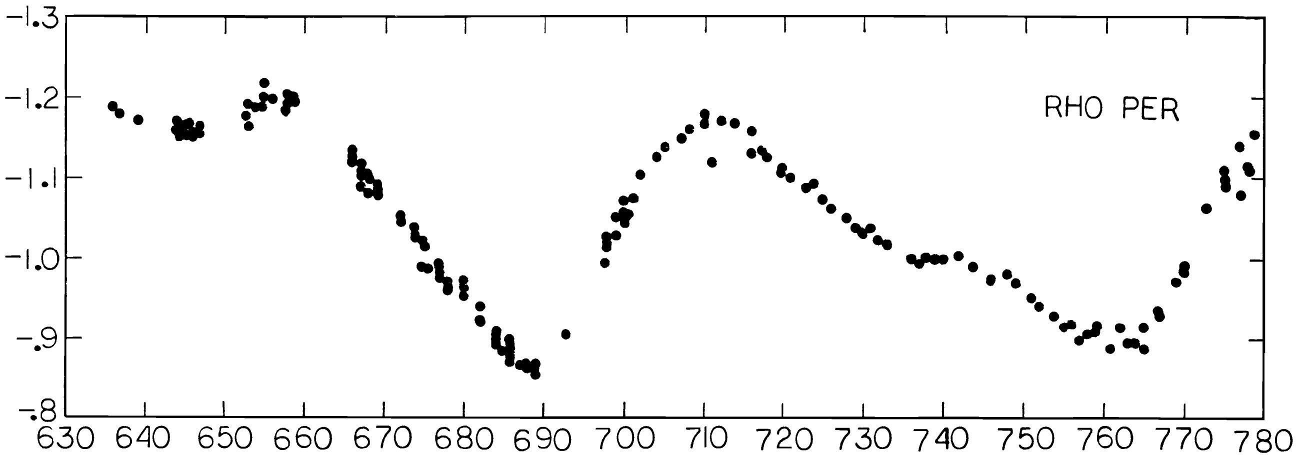

Fig. 3. Light curve of the semiregular Rho Per taken by the APT telescope of Fairborn Observatory West.

III. CURRENT STATUS

Once full operational status was achieved on the APT at Fairborn Observatory West, plans were immediately laid for two "second generation" APT's to be placed at Fairborn Observatory East. These second generation APT's were about to go into operation as this chapter was being written.

The second generation APT electronics has been completely redesigned to make it highly reliable, low in cost, and as simple as possible. The heart of the system is a small single-board computer, the 6809 microprocessor-based PT69 system manufactured by Peripheral Technology. It is available as either a board for about $300 (you add your own drives, power supply, and cabinet), or as a complete computer for about $1000. The main part of the specialized control electronics is contained on a 4 x 6 inch card. This is currently a wire-wrapped card, but we hope that it can be made available as a PC card to the astronomical community at cost in 1985. The other part of the electronics is a high-speed stepper driver. Three of these drivers are required per system (RA, Dec, and roof). Currently, these are point-to-point wired perf boards, but we hope to make these also available as PC boards. The prototype 2nd generation electronics is shown in Figure 4 at the Fairborn Observatory East during checkout.

The second generation software is very similar to the original software except that changes were made to accomodate the redesigned electronics. Over half the "procedures" (the control software is written in modules called "procedures") remained totally unchanged, while many of the others required only minor modification. Perhaps the largest change was to use a relatively short assembly language routine to control the ramping of the stepper motors. This allowed considerable hardware simplifications.

One of the new APT's at Fairborn Observatory East is quite similar to the original APT at Fairborn Observatory West. They both use 32-inch diameter aluminum disks driven by steppers via an antibacklash worm gear, sprocket, and chain. A somewhat finer pitch chain was used on the new APT, and commercially available gearboxes (from Winfred Berg Co.) were employed. A yoke instead of a fork mount was used due to the availability of two appropriately placed piers. Also, a 10-inch Schmidt-Cassegrain optical assembly was used (a Celestron C-10) instead of a 10-inch Newtonian, since the C-10 optics were readily available and it has a low moment of inertia. The photometer used on this system is an Optec SSP-3, and the system will be used in the near IR as will be described shortly. The system is shown in Figure 5.

The other new APT at Fairborn Observatory East is a totally new design by DFM Engineering. This research mounting was specifically designed for microcomputer control and low cost (Ref. 14). It uses two 15-inch diameter steel disks and friction contact rollers for highly precise, backlash free, rigid drives. This same approach is used on a number of large, modern telescopes such as the new 2.4-meter currently being installed at Kitt Peak. The key feature of this

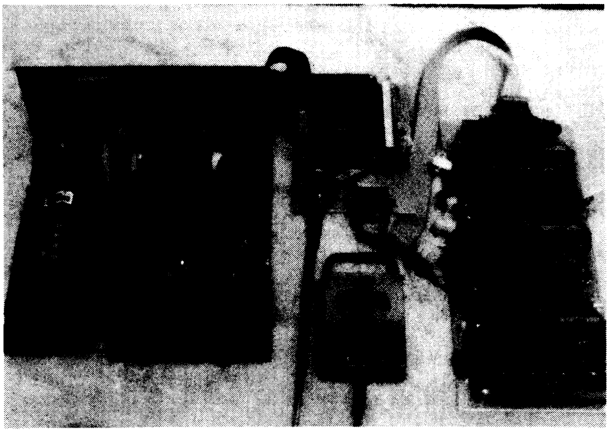

Fig. 4. Prototype of the 2nd generation APT electronics during checkout at Fairborn Observatory East. Simplifications in the design have greatly reduced the cost and improved the reliability.

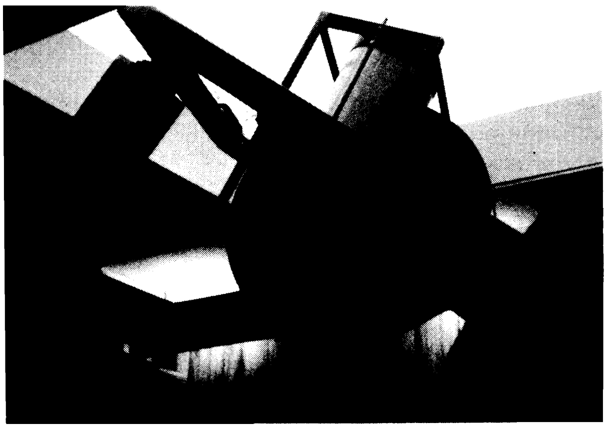

Fig. 5. The yoke mounted APT at Fairborn Observatory East, in Ohio. This system will primarily by used for near IR observations.

mounting is that it is available commercially at a relatively low cost. As will be described later, the mount is also available as part of a complete microcomputer controlled telescope which is well suited for APT operation. The system consists of the DFM Engineering mount, a Meade Instruments 10-inch Schmidt-Cassegrain optical assembly, a THORN EMI Gencom STARLIGHT-1 photon counting photometer, and the 2nd generation APT control electronics designed by one of us (Boyd). This APT is shown in Figure 6.

As mentioned above, DFM Engineering makes a complete microcomputer-controlled telescope which is ideally suited for APT operation. Their standard version consists of the mount already mentioned, an Apple-based control system, and a 16-inch (0.4-m) Cassegrain optical assembly with motorized secondary focus. The telescope control software is provided by DFM Engineering, and it can be readily commanded in absolute coordinates by user programs. Besides the standard 16-inch Cassegrain system, the system can alternatively be provided with a Meade 10-inch or Celestron 14-inch Schmidt Cassegrain optics. Figure 7 shows the complete DFM Engineering system with the Meade 10-inch optics.

IV. CURRENT STATUS: FAIRBORN OBSERVATORY PROGRAMS

As this chapter is being written, the APT at Fairborn Observatory West was about to begin its 4th quarter of operation. The observing program remains one of known and suspected RS CVn binaries, Zeta Aur long-period eclipsing binaries, AAVSO program semiregulars, and assorted other stars placed on the program for one reason or another. Generally, once a star is on the program, it is easier to leave it on than to take if off. The observing program on this APT has paved the way for the reduction, analysis, and publication of APT observations. It has, to say the least, kept all three of us busy!

The DFM Engineering/Meade Instruments APT at Fairborn Observatory East is being used in a program devised by Francis C. Fekel Jr. This program consists primarily of a large number of spectroscopic binaries with a wide range of rotation periods. The program will attempt to determine how slowly stars can rotate (in synchronism) and still exhibit the starspot phenomena. In the process it is expected that a number of new RS CVn-type binaries will be discovered. The photometer used in the program will be the THORN EMI Gencom STARLIGHT-1 using only the V band.

The yoke-mounted APT will be observing late-type variable stars in the near IR. In a cooperative program with Robert F. Wing, stars of spectral class M5 or later, not known to be variable, will be observed to determine how late a spectral type can be found without significant variability. Again, an important by-product will of necessity be the discovery of many new variable stars. A number of known Mira-type variables will also be observed.

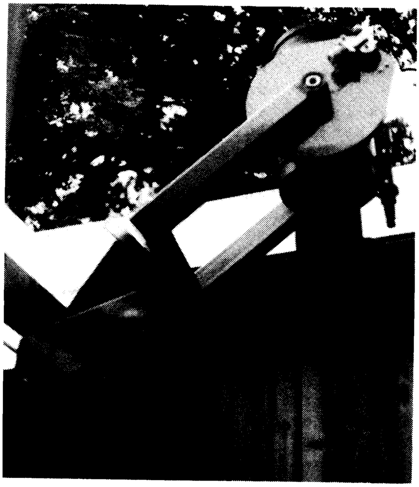

Fig. 6. The DFM Engineering/Meade Instruments APT at Fairborn Observatory East. Both the mount and the optics are available from commercial firms at modest cost.

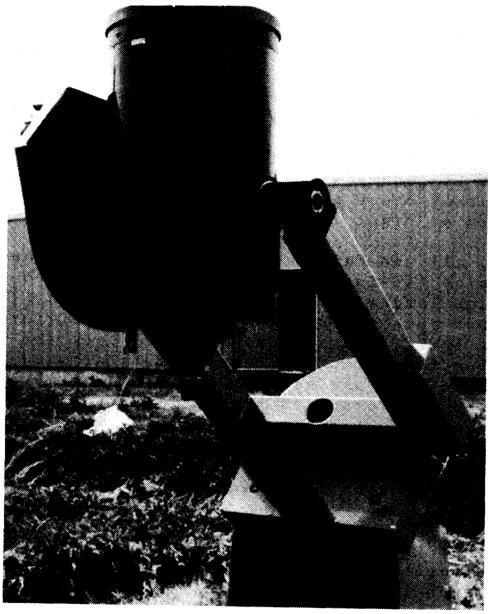

Fig. 7. The complete DFM Engineering microcomputer-controlled research telescope. The Apple computer, software, etc. are all included.

V. THE FUTURE OF AUTOMATIC PHOTOELECTRIC TELESCOPES

It is always hazardous to discuss the future, especially in a new field being hotly pursued by a number of different investigators. This is certainly the case for APT's, so we will limit the risk by restricting ourselves to future developments we have investigated or expect to participate in.

Perhaps the most important future development will be the application af APT's by a number of different investigators to various classes of variable stars, surveys, etc. The primary advantage of APT's is not that they do what is already being done more efficiently, although this is true in some cases, but that they can be applied to problems that no one would have attempted before APT's became available. Making the APT technology readily available to all will, we believe, make the efficient use of APT's possible.

As mentioned earlier, we hope to have available in 1985, PC cards for an APT system for those that wish to build their own. The complete APT software has been described and listed, as has the electronics hardware (Ref. 3). This description takes four chapters and a very large Appendix in a book. Also mentioned earlier, DFM Engineering can provide a complete off-the-shelf microcomputer-controlled telescope that is ideal for APT operation. We believe that these developments will aid in making APT technology readily available to all.

An APT does not, of course, require visual identification or centering of stars. All that is required is that the star be "seen" by some type of photometer. By operating at K-band, we hope to be able to do near IR APT photometry of variable stars during the day. This is a cooperative project with Jerry Persha at Optec, who is developing the K-band photometer. The system will be used to observe about 100 of the brightest (K-band-wise) variable stars. As might be expected, most of these are Mira variables. A telescope will be shared with a "night time" photometer.

To date, all the Fairborn Observatory APT's have been of very modest size (10-inch). There is, however, no inherent reason why much larger APT's could not built. While light gathering power goes up as the square of the mirror diameter, the moment of inertia goes up as approximately the fifth power. Keeping the moment of inertia within bounds so that the fast dynamic response needed for efficient APT operation can be achieved, has occupied some of our thoughts. A large, ultra lightweight/low inertia, and low-cost APT seems possible, and the application of such an instrument to a routine and large-scale program of quasar and BL Lac obserevations remains an important goal of the Fairborn Observatory.

At present, the largest "collection" of APT's is at the Fairborn Observatory East, with two. There is , however, no reason why a much larger number of APT'S could not be assembled at a single site. Such an assemblage could, as suggested by Morris Aizenman, be called an "APT Farm". There are two main advantages that an APT Farm would have. First, a single operator/engineer should be able to operate and maintain a dozen or more essentially identical APT's at a single site. Second, it would cost very little more to have the site be one that is "climatically overprivileged", i.e. has an unusually high percentage of photometric nights (and days). A single, well-placed APT farm could have a major impact on observational photometry.

Acknowledgements

In last year's chapter in Volume I of "Advances in Photoelectric Photometry" we pointed out that we were not the first to develop or apply small automatic photoelectric telescopes. Arthur D. Code has kindly made additional details available to us on the truely pioneering APT developed at the University of Wisconsin in the mid 1960's. Not only was this a completely automatic system (Ref. 15), but they somehow managed to operate it with only 4K of RAM (memory), a major achievement in itself! The more recent development by Skillman (Ref. 16) has also been inspirational, and it continues to gather data on short-period variables.

During the past year a considerable number of astronomers from around the world have freely suggested many ideas for the application and refinement of APT's. We would like to express a special thanks to Morris Aizenman, Arthur Hoag, Kent Honeycutt, Ronald Kaitchuck, Frank Melsheimer, Edward Olson, John Percy, Jerry Persha, George Roberts, Douglass Sauer, Robert Stencel, Mark Trueblood, and Robert Wing, and to all the many others who were so helpful.

REFERENCES

1. Boyd, L.J., Genet, R.M. and Hall, D.S. (1984) IAPPP COMMUNICATIONS, 15, 20.
2. Boyd, L.J., Genet, R.M. and Trueblood, M. (1984) Telescope Making, 22, 28.
3. Trueblood, M. and Genet, R.M. (1984) "Microcomputer Control Telescopes", Willmann-Bell, Richmond, VA.
4. Boyd, L.J., Genet, R.M. and Hall, D.S. (1984) I.B.V.S. Number 2511.
5. Boyd, L.J., Genet, R.M. and Hall, D.S. (1984) IAU Commission 27 Archives of Unpublished Observations of Variable Stars, File No. 131.
6. ----------(1984) I.B.V.S., in press.
7. ----------(1984) IAU Commission 27 Archives of Unpublished Observations of Variable Stars, File Number not yet assigned.

8 to 12. Boyd, L.J., Genet, R.M. and Hall, D.S. (1984) I.B.V.S. in press.

13. ----------(1984) Astrophys. Spc. Sci., in press.
14. Melsheimer, F. and Genet, R.M. (1984) IAPPP COMMUNICATIONS, 15, 33.
15. McNall, J.F., Miedaner, T.L. and Code, A.D. (1968) A. J., 73, 756.
16. Steillman, D.R. (1981) Sky and Telescope, 61, 71.