THE DESIGN AND STANDARDIZATION OF A THREE COLOR ASTRONOMICAL PHOTOMETER

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THREE COLOR ASTRONOMICAL PHOTOMETER

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PREFACE

Astronomical photometry, a specialized field in the broad area of optical astronomy, has experienced marked development during the past twenty-five years. General advances in other areas, such as solid-state electronics and data processing, have been utilized by astronomers to improve both precision and efficiency in photometric work. Throughout this period of rapid change, one unique aspect of astronomical photometry has remained essentially constant. The contributions of interested and capable amateurs are still accepted and appreciated by professional astronomers, particularly in the area of variable star photometry.

This feature sets astronomical photometry apart from most other specialized endeavors in the physical sciences. As a result, certain pedagogical advantages accrue which are not available to all scientific disciplines. Some of the features of variable star studies which are particularly appropriate for inclusion in a high school science program are discussed in the introductory chapter.

This paper is concerned primarily with application of the principles of astronomical photometry to the problem of developing three color photoelectric instrumentation for use in secondary school astronomy programs. Design considerations place emphasis on small telescope applications, such as those likely to be found in high schools and four-year colleges. The photometer developed in this study has been installed at Enid (Oklahoma) High School where it is being used for variable star studies.

Calibration procedures, for standardizing the instrument on the Johnson-Morgan UBV System, have been carefully outlined in the text, and a preliminary calibration run was carried out. On the basis of these results, recommendations are made concerning future programs for completing the calibration.

I would like to express my appreciation for the assistance and guidance provided by the members of my advisory committee: Dr. H. E. Harrington, who, despite his many duties as Head of the Physics Department, served as Chairman until his retirement last year; Dr. W. W. Marsden and Dr. J. E. Susky, who contributed personal interest and advice on the more formal part of my program; Dr. D. L. Rutledge, who was always available for counsel, and whose advice on general procedural matters has been particularly helpful; Dr. L. W. Schroeder, whose thoughtful suggestions and sincere interest in the problems of teaching astronomy and physics provided constructive guidance in the definition and treatment of the dissertation topic.

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CHAPTER I

NATURE AND SIGNIFICANCE OF THE PROBLEM

Optical astronomy, a unique blend of applied mathematics and the physical sciences, is the object of much scholarly work at the graduate and post-graduate levels. Furthermore, some of the specific categories in the general area of optical astronomy require skills which are well within the capabilities of amateurs. Usually, the primary prerequisite is continuing interest.

A classic example is the study of variable stars. This field of optical astronomy has always leaned heavily on the work of intelligent and enthusiastic amateurs. Modern developments in electronics and computer technology have placed powerful tools for observation and data handling at the disposal of all variable star observers. In particular, photoelectric detectors and linear amplifiers have been developed to the point where it is feasible to equip telescopes of relatively small aperture for variable star work. The net result is that the properly motivated and equipped amateur is capable of work which results in meaningful contributions to general knowledge in the field of variable stars. This characteristic of photoelectric astronomy is a powerful source of motivation which tends to generate and support student interest in this area.

Given the heuristic nature of photoelectric astronomy, the pedagogical applications become apparent. It is suggested that active student involvement in photoelectric stellar astronomy is a vehicle whereby the student, with proper guidance, may gain insight concerning the nature of science. The literature of science education abounds with statements pointing to the contemporary relevance of such understanding:

> To an increasing degree, education goes beyond the secondary level. To an increasing degree, society becomes specialized and technical. To an increasing degree, important public questions require a knowledge and understanding of science (1).

> In the present day era of science and technology it would seem that an essential part of liberal arts education involves an understanding and appreciation of the nature of scientific inquiry. It is as important to know how the scientist works as it is to know what he has learned. In order to gain these insights the student must experience the scientific process for himself. It is only through such experience, however limited, that the nonscience major can hope to gain a genuine and long-lasting understanding of science - one devoid of mystery and the image of the strange man clad in a white jacket (2).

It has been the writer's experience that involvement of the student in the process of scientific inquiry is seldom achieved by the "traditional" lecture demonstration accompanied by verification-type laboratory exercises. Student experiences should be structured in such a way as to give the participant insight into the nature of the experimental process, while at the same time allowing him to achieve a better understanding of some factual aspect of the discipline. The following writer, referring specifically to physics, points to laboratory experience as a means of guiding the student in his approach to a more general understanding of science.

> The study of physics must not be divorced from the phenomena....The laboratory should definitely provide the student an opportunity to know physics as a process of inquiry leading to theory, not as a mere accumulation of inert information....Learning to know is not the whole of laboratory work; acquiring the ability to feel what the scientist feels is equally important. In the laboratory, the student should be a 'physicist for a day.' He should encounter the joys

> and sorrows of experimenting, elation and despair. He should come upon the unexpected, run up blind alleys, and work himself out of tight places. He should experience the sight and sounds, the smells and emotions of the laboratory. Having had such experience, the student can claim a kinship, however remote, with the physicist and will have an insight into the scientific enterprise which no amount of mere lecturing can give him (3).

The biological and physical science curriculum reforms which emerged in secondary schools during the mid 1950's and early 1960's were designed to promote an understanding of the process dimension of the discipline. Thus, laboratory experience of the type mentioned previously plays an integral role in such courses.

It is here proposed that student participation in research type activities, such as the photoelectric observation of variable stars, tends to reinforce the general scientific concepts which have been stressed in the properly conducted introductory courses. It should be understood that student research participation is not necessarily bound by formal prerequisites. The necessary technical skills and specialized formal training vary among the disciplines. It has been the author's experience, dealing with secondary school pupils, that the sufficiently motivated student is able to amend his technical and formal training to meet the needs of the situation. Powers (4) has described similar applications at the college level.

The specific application of interest here is stellar photoelectric photometry. For the past several years, both during and following his tenure as physics instructor at Enid (Oklahoma) High School, the author has enjoyed the use of the facilities at the Enid High School Observatory. During this time student participation has resulted in several projects in the area of photoelectric photometry. Most recently, the primary emphasis has been stellar photometry with particular emphasis on time-of-minimum determinations for eclipsing systems.

It is expedient at this point to specify the particular characteristics of this endeavor which make it a suitable activity for student participation. One of the most important features is that of self motivation. The basis of this characteristic is at least two-fold. First, the result of properly processed observations is a time of minimum light for the observed stellar system. This quantity is meaningful and valuable to the professional astronomer. Thus the results of a carefully done minimum determination represent a real contribution to knowledge in the field. In addition, the techniques which are used to reduce the raw data are readily programmed for computer processing. Thus, the student may become acquainted with the fundamentals of computer data handling in the context of a real problem. This "fringe benefit" - acquisition of computer methods and programming experience - finds application in almost all professions. Thus, student interest, once ignited, is readily maintained.

Another characteristic of variable star work which makes it particularly appropriate for student involvement is flexibility in the required mathematical preparation of the participant. After reduction, the data may be treated by various methods to determine a time of minimum. The methods in use range from the graphical tracing paper technique developed by Szfraniec (5) to more quantitative computer oriented methods such as that of Kwee and Van Worden (6). Thus, in terms of mathematical background, the activity is equally well suited to high school students and college undergraduates.

Any proposed research participation program should be examined not only in terms of feasibility with respect to interest and background of the students, but also with regard to value in terms of general educational goals. It has been previously stated that the photometry of variable stars is an activity which enhances the participant's understanding of science as a method of critical inquiry. Although a detailed analysis of the proposed activity in terms of educational goals is beyond the scope of this paper, it is appropriate to note certain broad objectives which are compatible with this program.

Good science instruction at any level should be designed to aid the student in the development of certain general skills. Included among these are: the identification of the problem in a novel situation; the ability to make relevant observations; the ability to make approximations and draw valid conclusions from observations and data; proficiency in suggesting new lines of investigation based on observations; formulation of a simple scientific model and use of the model to make logical predictions. In addition, the student should be able to demonstrate his understanding of fundamental principles by applying those principles in an unfamiliar situation. In short, the creative use of these skills and abilities constitutes a significant part of scientific inquiry.

As a pedagogical tool, the photoelectric study of variable stars engenders most, if not all, of the aforementioned skills. More specifically, the choice of a program star and the planning of an observing schedule require the student to recall rather carefully his basic knowledge of timekeeping and the earth's motion in space. This phase of the project also involves predictions based on an assumed model for the light variation of the program star. In planning specific observation procedures, the student must identify background skylight and atmospheric attenuation of starlight as problems to be reckoned with, and methods of observation are designed accordingly. Processing of raw data requires the application of elementary mathematical formulations, including graphical methods of representation. Interpretation of refined data leads to descriptions, in varying degrees of detail, of the stellar system whose light variations are being studied. In any case, this phase of the operation invariably involves choice of a model Depending on the amount of detail included in the analysis, the model may be used to predict future behavior of the system, and it thus serves as a basis for design of future observing programs.

In summary, it has been argued that student participation in astronomical photometry is feasible in terms of participant motivation and background, and it is meaningful with regard to reinforcement of certain general aspects of scientific inquiry. The design, installation and calibration of instrumentation necessary for such a program of student research is the topic of the major part of this paper. The specific system to be described herein has been installed in the Enid High School Observatory where it is now being used by secondary school students for variable star studies.

It is expedient, at this point, to outline qualitatively the general considerations included in the design and calibration of a photometric system. The general problem of astronomical photometry is to extract information about the stars or other celestial objects from the radiation which they emit. Usually, the photometric study is concerned with brightness as a function of wavelength and/or brightness as a function of time.

The measurement of brightness implies the use of a receiver to gather the radiation, a detector to quantitatively register the presence of radiation, and some means of displaying the output of the detector. The interactions of radiation with interstellar material, the earth's atmosphere, and the detection-display instrumentation alter the measured brightness. Thus the measured brightness is not only a function of source-related parameters, but also it depends on factors external to the source: e.g., atmospheric extinction and instrumental transmission characteristics. Hence, the reduction of observational data should take into account those effects which are not directly related to the source. In order that this be done in a meaningful fashion, it is necessary for the observer to familiarize himself with the spurious effects and conduct the experimental work in such a way as to measure, control, or minimize the influence of these effects on the measured brightness.

The degree to which one tries to account for all of the factors affecting the brightness depends on the nature of the study undertaken. Much work, particularly the study of variable stars, is done in what might be called medium bandwidth spectral regions. As defined by Hardie (7), "medium bandwidth" refers to photometric systems in which the ratio of the half-intensity bandwidth to the effective wavelength is of the order of 0.1 - 0.2. In systems of this type, both magnitude and color determinations are dependent on the choice of components, such as filters and photocell, which are used in the detection-display instrumentation. In practice, each assembly of telescope, filters, detector, and amplifier determines a <u>unique</u> system for the measurement of stellar magnitudes and colors. This unique system is, by definition, the observer's <u>natural</u> system.

For the purposes of comparison, it is essential that natural magnitudes and colors, as determined by various observers, be referred to a standard system. A widely accepted standard for UBV photometry is the system of Johnson and Morgan (8), which makes use of glass filters and the RCA 1P21 photomultiplier. By judicious choice of filters and detector, it is possible to assemble a natural system which closely matches this standard.

In order to effect transformation of observed quantities to those which would have been observed with the standard system, one makes use of so-called "standard stars." These stars have accurately known magnitudes and colors as determined by their observation with the standard system. The standard stars are observed to obtain natural magnitudes and colors, and these data are used in conjunction with the known standard values to obtain transformation relationships for expressing natural magnitudes and colors on the standard scale. It can be shown that if the natural and standard systems are closely matched physically, the transformation equations are linear (7). In addition to providing concise transformations, a system which is closely matched to the standard system permits the use of standard stars for rapid and accurate determination of extinction by the method of Hardie (7, 9).

The kinds of measurements of interest in the present case include: (1) comparative brightness measures of different stars in the same spectral region; (2) brightness measures of a particular star in several rather widely separated spectral regions; (3) brightness measures of a particular star (as in 2) as a function of time. The reduction of data obtained in medium bandwidth photometry of this type involves essentially two steps: (a) a correction for atmospheric extinction; (b) transformation from the observer's system of magnitudes and colors to a standard system of magnitudes and colors. This requires experimental determination of the atmospheric extinction coefficients and the constants in the equations of transformation.

The development of a UBV system of photometry for the Enid High School Observatory explicitly involves: (1) design of the photometer; (2) experimental determination of the transformation equations relating the Enid system to the system of Johnson and Morgan; (3) measurement of second order atmospheric extinction coefficients for the E. H. S. Observatory.

CHAPTER II

THE HISTORY OF ASTRONOMICAL PHOTOMETRY

Introduction

Most of man's knowledge of the universe, external to the minute patch on which he resides, has resulted from careful study of radiation from extra-terrestrial sources. A large portion of this radiation is electromagnetic in nature, and the essential problem is extraction of various bits of information carried by the radiation quanta. Classical astronomy, being concerned primarily with position of the stars, sun, moon, and planets, neglected a large fraction of the information carried by light.

Details of the physical environment in which the quanta originated can be inferred from a study of brightness as a function of wavelength. Ideally this would involve spreading the light from a particular star into a spectrum and measuring brightness in each resolvable wavelength interval. In practice, this procedure (spectrophotometry) has not been widely followed. Compared to other methods of analysis it is costly in terms of time, and due to the fact that energy is distributed among the various spectral regions, the method is somewhat impractical for the fainter stars.

Another technique, measurement of "total brightness" of stars and other objects does not yield as much detailed information as spectrophotometry. However, "total brightness" measures are comparatively easy to obtain and this is the ordinary use of the term photometry in astronomy. Since atmosphere and instrumentation impose limits on the spectral region observed, it is not actually possible to measure total radiation (including all wavelengths) for a given star. However, techniques have been developed which utilize these apparent limitations. In order to understand the form and application of these techniques in contemporary practice, it is expedient to consider the evolution of modern astronomical photometry.

Three principal sources were used in preparation of the abridged historical sketch which follows. H. J. Smith (10) presents an overview in Chapter I of Photoelectric Astronomy for Amateurs. The series of articles by H. F. Weaver (11) provides a well documented comprehensive treatment through 1946. The chapter by H. L. Johnson (12) in Basic Astronomical Data treats modern photoelectric systems comprehensively.

It is convenient to consider the development of astronomical photometry in three periods, each of which is clearly distinguished by the type of detector used, although this criterion does give rise to some chronological overlapping. The earliest photometric measures were made visually; i.e., the eye served as a detector. In photographic photometry, photographic plates are used to detect and measure stellar radiation. Photoelectric photometry, the most widely practiced contemporary method, employs a photosensitive device such as a photomultiplier to register quantitatively the presence of starlight.

Visual Photometry

During the earliest part of the visual period, estimates of stellar brightness were made by unaided eye. Later, the telescope was used, and finally photometric devices were developed for use with the telescope. Notwithstanding the development of instrumentation which permitted more quantitative uniformity in the measurement of stellar brightness, the most important single accomplishment during the visual period was the mathematical definition and the practical implementation of an absolute brightness scale.

One of the earliest recorded attempts to compare star brightness is credited to Hipparchus who divided the stars into six groups. First magnitude stars were the brightest; second magnitude stars appeared, on the average, about half as bright as the first, and so on down to the sixth magnitude for the faintest stars visible to the unaided eye. Hipparchus' catalogue of stellar magnitudes, apparently compiled c. 120 B.C., was adopted and expanded by Claudius Ptolemy. This catalogue was included in Ptolemy's Almagest, and it served as the basic reference of stellar astronomy for nearly two thousand years.

Following the invention of the telescope and its introduction, in 1609, as a tool of astronomical research, Ptolemy's system of magnitudes was extended to include the fainter "telescopic" stars. Not only did it then become necessary to make use of magnitudes greater than six, but also greater precision in measurement of stellar brightness gave rise to the necessity of subdividing the magnitude scale.

Shortly before 1800, Sir William Herschel devised a symbolic step-degree method of estimating stellar brightness. This involved short sequences of stars which were ordered according to apparent brightness, the degree of difference between successive sequence members being indicated by means of symbols. Argelander later made use of a similar scheme for estimating the light variation of variable stars. Similar approaches were used by other observers including Heis, Gould, Schönfeld, and Thome during the second half of the nineteenth century. The resulting catalogues, which included the various Durchmusterungen, contained positions and magnitudes for more than a million stars.

Throughout most of this part of the visual period no standard scale of brightness existed, and each observer, though he referred to previous results, essentially designed his own scale. Hence, rather large systematic differences existed between the results of different observers. Table I contains a comparison of the magnitude scales established by some of the observers of this period. The first column of the table headed M gives the magnitude for the observer listed to the right. The entries in the body of the table give the corresponding values in terms of the modern magnitude scale.

The development of photometric measuring instruments resulted not only in more precise individual magnitudes, but also in increased accuracy of scale determination. The higher precision which resulted from these developments brought increased efforts to devise a decimal subdivision of the magnitude scale. This eventually led to mathematical formulation of the magnitude scale.

The first application of a photometric instrument to an astronomical problem is attributed to P. Bouger who, in 1725, compared the brightness of the sun and moon to a standard candle by means of a simple illumination photometer. About fifteen years later, A. Celsius and A. Tulenius of the Upsala Observatory used a crude extinction photometer to estimate stellar magnitudes.

Instrumental photometry had been dormant for nearly a century when, in 1836, the work of Sir John Herschel heralded a period of rapid

TABLE I

A COMPARISON OF SOME VISUAL MAGNITUDE SCALES

M	Ptolemy	Argelander	Heis	Gould
1.0	1.0	0.6	0.6	0.8
2.0	2.4	2.3	2.3	2.3
3.0	3.6	3.4	3.4	3.3
4.0	4.5	4.3	4.3	4.2
5.0	5.0	5.1	5.1	5.0
6.0	5.3	6.0	6.1	5.9

Source: (11)

advances. The most significant instrument developed during this period was the Zöllner photometer. This device, which was introduced shortly after 1850, was designed to permit comparison of the focal plane image of a real star with that of a laboratory standard source. The apparent brightness of the standard source was controlled in a precisely determined way by the relative orientation of two Nicol prisms. Zöllner completed an extensive series of measurements with the instrument in 1861. In following years, a number of observers including E. C. Pickering at Harvard, and G. Müller and P. Kempf of the Potsdam Observatory made effective use of Zöllner-type photometers.

Starting at Harvard in 1871, Pickering's experiments with various photometers, each of which utilized the principle of the Zöllner instrument, led to the development of the meridian photometer, the final form of which was completed in 1898. Stars as faint as thirteenth magnitude could be measured with this instrument, and it was used to investigate variable stars, to establish standard sequences, and in various other programs on faint stars. Observations made during the years 1879-1902 were collected in _Annals of the Harvard College Observatory_, Volume 50, the _Revised Harvard Photometry_, which contains visual magnitudes for stars brighter than magnitude 6.5 (9110 stars), and _Supplement to the Revised Harvard Photometry_, Volume 54, which contains visual magnitudes for 36,000 additional fainter stars.

During the years from 1886 to 1905 G. Müller and P. Kempf, of the Potsdam Observatory, used a Zöllner photometer to determine magnitudes of all stars having north declination and brighter than magnitude 7.5 on the _Bonner Durchmusterung_ scale. This work, characterized by a carefully planned and meticulously executed observational program, resulted in the Potsdam Durchmusterung, the most accurate of the more extensive catalogues of the visual period.

Taken together, the Revised Harvard Photometry and the Potsdam Durchmusterung, published shortly before 1900, contained visual magnitudes for more than 40,000 stars to an accuracy better than 0.1 magnitude. Table II, which is arranged according to the same scheme used for Table I, exhibits the degree of internal accuracy achieved by the more recent visual observers.

The development of objective instrumental methods supported a growing need for a more rigorous definition of the magnitude scale. Originally, the magnitude unit was based on the intensity of the physiological sensation produced by observation of a luminous object, and Ptolemy's magnitudes were essentially estimates of visual sensation intensity.

In 1859, Fechner suggested that the difference in retinal response produced by two stars differing only in brightness is dependent only on the ratio of the stellar intensities. This concept may be stated mathematically as follows:

$$m_1 - m_2 = (1/\log \rho) \log (I_2/I_1)$$

where ρ is a constant, m_1 and m_2 represent the magnitude (retinal response) of stars 1 and 2 respectively, and I_1 and I_2 represent the intensity of light received from those respective stars. Although it is now known that this formulation is not correct for all intensities, this form of Fechner's Law was adopted and persists in modern photometric work.

TABLE II

A COMPARISON OF THE MOST RECENT VISUAL MAGNITUDE SCALES

M	Oxford	Harvard	Potsdam
1.0			0.74
2.0	2.18		1.74
3.0	3.14		2.74
4.0	4.06	3.92	3.74
5.0	5.03	4.94	4.74
6.0	6.2	5.99	5.77
7.0		7.06	6.80
8.0		8.14	
9.0		9.24	
10.0		10.25	
11.0		11.16	
12.0		12.06	

Source: (11)

From measurements of relative stellar intensities made during the latter part of the visual period, it was possible to evaluate Fechner's constant ρ. In 1879 E. C. Pickering adopted the value log $\rho = 0.400$ ($\rho = 2.512$) for the extensive series of photometric observations then in progress at Harvard. This particular value of ρ, which had been suggested by Pogson in 1856, was used quite generally by astronomers after its adoption by Pickering, and it was finally adopted by international agreement as the standard scale value to be used in all photometry. Thus, for two stars whose magnitude difference $(m_1 - m_2)$ is five, the intensity ratio (I_2/I_1) is one hundred. Accordingly, a magnitude difference of one corresponds to an intensity ratio of $(100)^{1/5} =$ 2.512. Magnitude scales defined in this way are formally designated as "Pogson Normal Scales."

If the Pogson Sclae is to be used to extend the magnitude system to brighter and fainter stars, it is necessary to set the zero point. The zero point of the North Polar Sequence, a set of about 100 standard stars, was chosen in such a way that magnitudes of A0 stars in the magnitude range 5.5 - 6.5 are, on the average, in agreement with the corresponding magnitudes of the Harvard Polar Sequence. The zero point of the Harvard system was determined by making the average magnitude of 100 northern stars agree with the average magnitude assigned those same stars by Argelander. Since Argelander's scale and zero point were essentially in agreement with Ptolemy's magnitudes, it is seen that choice of a Pogson Scale with the zero point defined as explained above preserved the general trend of the magnitude scale as defined by Hipparchus.

By 1900, the visual period had essentially come to a close. The work done in visual photometry after the start of the present century was, for the most part, in specialized areas such as double stars, variable stars, etc. The main reason underlying the truncation of visual work was the application of the photographic process to astronomical photometry. Not only did photographic methods terminate visual photometry, but also they dominated the entire field during the first quarter of the present century.

Photographic Photometry

Photographic methods were introduced in 1844 by Fizeau and Foucault who compared photographically the brightness of the sun to that of a carbon arc. A few years later, in 1850, the first stellar photograph was made at the Harvard College Observatory under the direction of W. C. Bond. Using daguerrotype plates and the Harvard 15-inch telescope, Bond was able to obtain images of brighter stars, such as Vega, but in general the fainter sources could not be photographed regardless of the duration of the exposure. Thus, the experiments were discontinued.

By 1857, plate sensitivity had been improved to the point where Bond found it worthwhile to renew his experiments in stellar photography. Based on the results of this second set of experiments with the 15-inch telescope, Bond (13) suggested that stellar magnitude is related to the following independent photographic quantities: image diameter (for a given exposure duration) and time required to produce noticeable chemical action. Continuing his investigation Bond (14) concluded that the diameter (d) of a stellar photographic image could be represented as a function of exposure time (t) by an expression of the form:

$$d^2 = At + B$$

where A and B are constants. Further, he suggested that the ratio of exposure times required for stars of different magnitudes to form images of the same size, or, alternately, that the ratio of the reciprocals of the areas of objectives affording images of equal diameter in equal exposure times, would be a measure of the photographic magnitudes of those stars.

For a number of years following the pioneering work of Bond, little was done in the field of photographic photometry as such. During the 1870's, significant improvements were made in photographic materials and general techniques. Then, in 1881 A. A. Common, using a newly developed gelatin silver bromide emulsion, photographed stars too faint to be seen visually in the largest telescope then in existence, and astronomical photography came of age.

In 1882, E. C. Pickering (15) started a preliminary investigation on the feasibility of using star trails obtained with a stationary camera to establish magnitudes. In general, the method involved comparison of the trails with a standard graded series of trails which was assumed to define a Pogson Scale. In view of the general success of the preliminary tests, a second series of photographic experiments was begun by Pickering in 1885. In the same year, J. C. Kapteyn joined Gill of the Royal Observatory at the Cape of Good Hope for a photographic study of southern stars, and the Henry brothers began photographic experiments at the Observatory of Paris.

Although Pickering's method of trails proved to be unsatisfactory, his analysis provided considerable insight into some of the previously unforeseen difficulties associated with photographic photometry. One of the most important findings was the systematic difference between the magnitudes from one plate to another. Thus, the standard image scale could not be calibrated once and used directly for all future measurements. Also, it was noted that the camera behaved rather like the human eye in that the measured magnitude depended on the position of the image on the plate.

By the time Pickering had published thses conclusions, Kapteyn and Gill were well along in their work which was to result in the Cape Photographic Durchmusterung. Also, the preliminary success of the Henry brothers had influenced the French Academy of Science to assemble an international congress, in April 1887, for discussion of the feasibility of producing a photographic chart of the entire sky. This chart was to be called the Astrographic Catalogue. Weaver (11) outlines, on page 292, some of the problems involved in this undertaking:

> The problems involved in seeing this ambitious program through to completion were undoubtedly not realized by the members of the Astrographic Congress at the time of the first meeting, or for many years thereafter. Not one of the smallest problems was the photometry involved in the construction of the catalogue. No photographic magnitude scale was available; the properties of photographic plates were poorly understood; the law of reciprocity was quite generally accepted. At the time of the first meeting of the Congress the papers dealing with Pickering's photographic researches, by far the most fundamental of that period, had not been published - the experiments had not even been completed. (Moreover, Pickering's work was criticized when it did appear, and seems to have been discounted rather generally.)

In addition to clarifying certain sources of error in photographic photometry, Pickering suggested the use of extra-focal images. Just before 1900, K. Schwarzschild of the Kuffner Observatory independently made the same suggestion and made a very careful study of the photometric uses of such images. With this type of record, the image diameter was of little importance since all images were the same size. Stellar brightness was determined by amount of darkening, or density of the image. In his earliest work, Schwarzschild made use of empirical equations in which the constants were evaluated from measurements of Type A stars of known visual magnitudes. The significance of this work is based on the fact that it represents the first extensive test of the extra-focal method. Also, it marks the beginning of extensive researches of this method by many other observers.

By 1899, Schwarzschild's theoretical studies of extra-focal stellar images had reached an advanced stage. In that year, he suggested the following functional relationship

$$S = f(I \cdot t^{p})$$

relating image density (S), intensity of incident light (I), exposure duration (t), and the Schwarzschild exponent (p), originally thought to be constant (16). These studies pointed to the complex nature of image formation on a photographic plate.

In general, as shown in Figure 1, the response of an emulsion to light is non-linear. There is a background density which appears in the developed emulsion regardless of the amount of exposure. As the total amount of light increases, image density rises slowly and enters the linear portion after the exposure has passed a certain threshold. Still greater amounts of light carry the exposure into the saturation region, where the density is constant or may decrease slightly with increased exposure. In general, astronomical applications are not restricted to the linear portion of the curve.

In 1906, Schwarzschild (17) presented his paper on magnitude determination, and the methods discussed therein have served as a basis

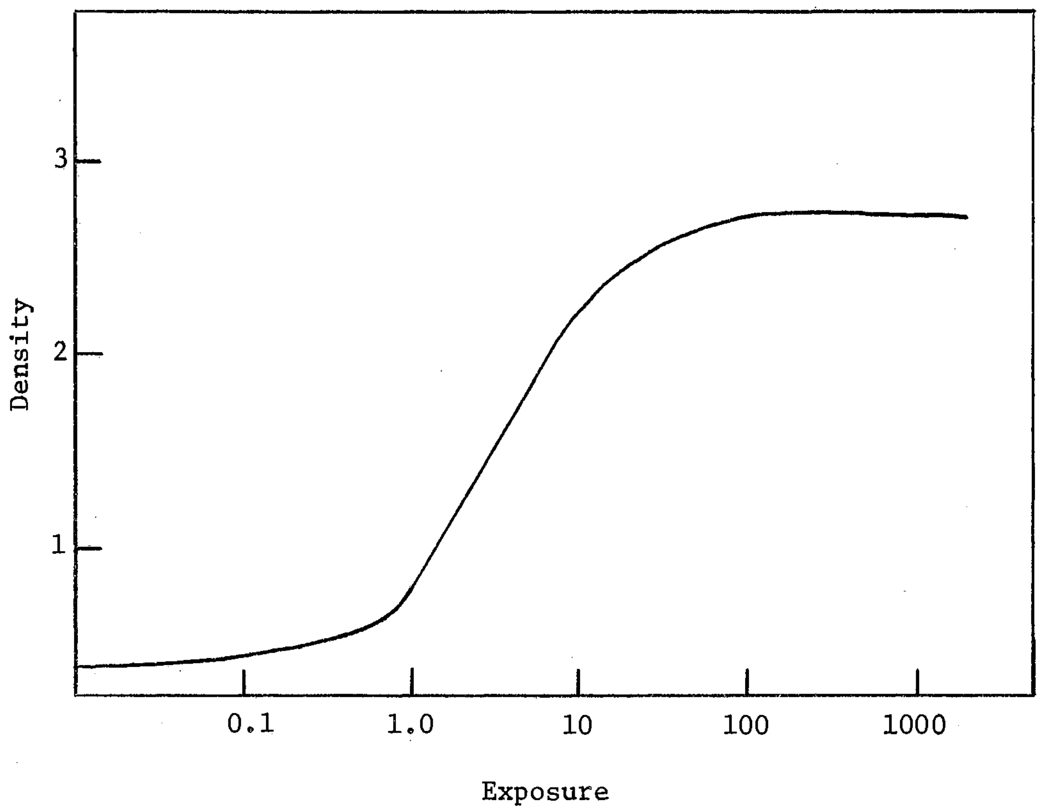

Figure 1. Response Curve of Typical Photographic Emulsion

for the establishment of all modern photographic magnitudes scales. Experimental work following that of Schwarzschild had provided, by 1910, a multitude of techniques for establishment of photographic magnitude scales. However, very little had been done toward standardizing the magnitude system.

Shortly before 1910, interest began to shift to the establishment of a fundamental magnitude scale defined by a series of standard stars. Such a standard scale could be transferred to any other area by photographing on one plate, with equal exposure times, the area in which the magnitudes were desired and the standard area. About 1906, Pickering had mentioned the successful application of such a procedure at Harvard using a standard sequence near the north celestial pole. In 1909, the method was described in detail, and Pickering (18) proposed as a standard scale a sequence of 47 polar stars for which magnitudes were then being determined at Harvard. Through cooperation of observatories having larger telescopes, it was planned to extend this magnitude scale to the faintest stars. Also, secondary standard sequences were to be established by comparison with the primary standard sequence of pole stars. In 1910, the Astrographic Congress adopted Pickering's North Polar Sequence as the primary standard sequence for establishing a magnitude scale, and the zero point was chosen to agree with the zero point of the Harvard visual magnitude scale. The task of establishing a completely satisfactory North Polar Sequence was immediately taken up at a number of observatories.

During the next decade, much careful experimental work was aimed at the establishment of a standard magnitude sequence. One of the leaders in this effort was F. H. Seares of the Mount Wilson Observatory.

In 1922 Seares (19), acting in the capacity of President of the Commission on Stellar Photometry of the International Astronomical Union, presented a detailed and critical analysis of photographic and photovisual magnitude scales based on the North Polar Sequence. Thus, in 1922 the magnitudes and colors of more than 100 stars comprising the North Polar Sequence were accepted by international agreement as definitive standards for photographic photometry all over the sky. In general, this standard sequence has served quite well, although there is a marked departure from a Normal Pogson Scale in the faintest magnitudes.

Concurrently with the development of photographic photometry in general came advances in more specialized related fields, one of the more active being photographic determination of colors. Soon after photographic methods became generally available, it was noticed that magnitudes determined from star images on photographic plates differed systematically from those determined by visual methods for a given star. This fact was cited by some observers during the early days of photographic photometry as one of the important reasons for not using the photographic process for photometric purposes. One of the earliest observers to recognize the importance of photography as a means of determining stellar colors, as well as magnitudes was Pickering (15) who stated on page 203:

> The photograph furnishes an excellent test of the color of a star, since on comparison with the visual brightness, the stars which are faint photographically may be assumed to be red and the bright ones blue. As the difference amounts to several magnitudes, it furnishes a test much more sensitive than that of the eye. Again, the method is applicable to the faintest stars visible, where the difference in color is quite imperceptible by any other means.

A qualitative understanding of these facts follows consideration of the different spectral responses of the eye and photographic emulsion to the distribution of energy in stellar radiation. To a first approximation, the radiant energy emitted by most stars follows a Planck distribution. As shown in Figure 2, both the quantity of energy and the distribution of energy are functions of temperature. For higher temperatures, the total energy is greater, and the wavelength of maximum intensity is shifted toward the short wavelength (blue) end of the spectrum. In general, the hotter the star, the bluer will be its integrated color, as predicted by the Planck expression for energy distribution ($B_\nu(T)$) as a function of frequency (ν) and absolute temperature (T);

$$B_\nu(T)d\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT}-1} d\nu .$$

The average eye responds most strongly to a narrow band of wavelengths centered about 5500 angstroms. The photographic emulsion, unless specifically treated, responds only to wavelengths shorter than about 4500 angstroms, and, due to limitations of atmosphere and optical components, the photographic wavelengths for most astronomical purposes are centered about 4200 angstroms. Thus, photographic and visual magnitudes are measures of intensity in different parts of the energy spectrum. A specific example is illustrated in Figure 3, which shows the Planck curves for two stars differing in temperature. Although the two stars have about the same visual magnitude, the hotter star is much brighter photographically.

Following Pickering's initial suggestion, Schwarzschild, in 1900, made a similar suggestion in regard to use of the difference between visual and photographic magnitudes as an accurate measure of a star's

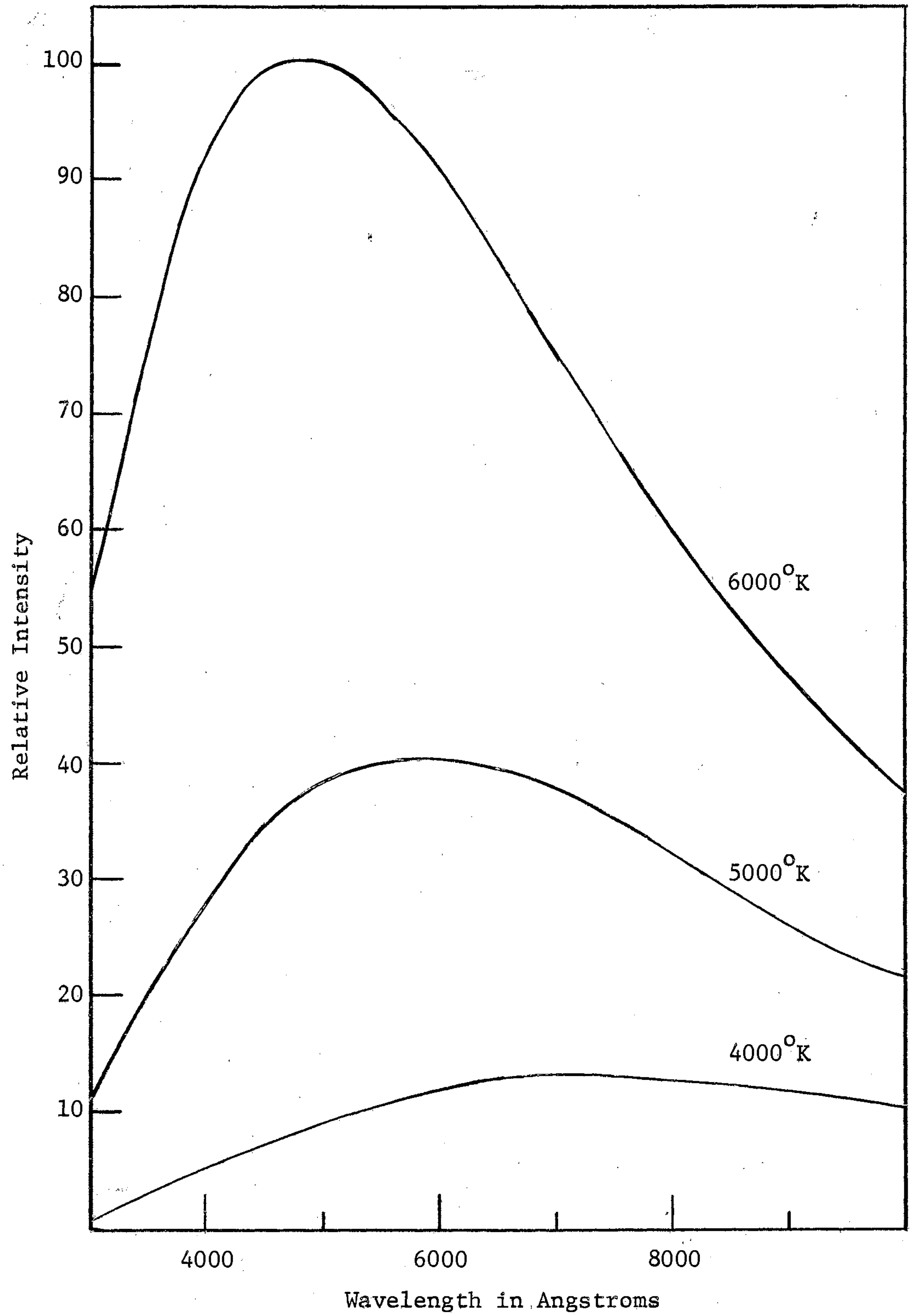

Figure 2. Black Body Radiation as a Function of Wavelength

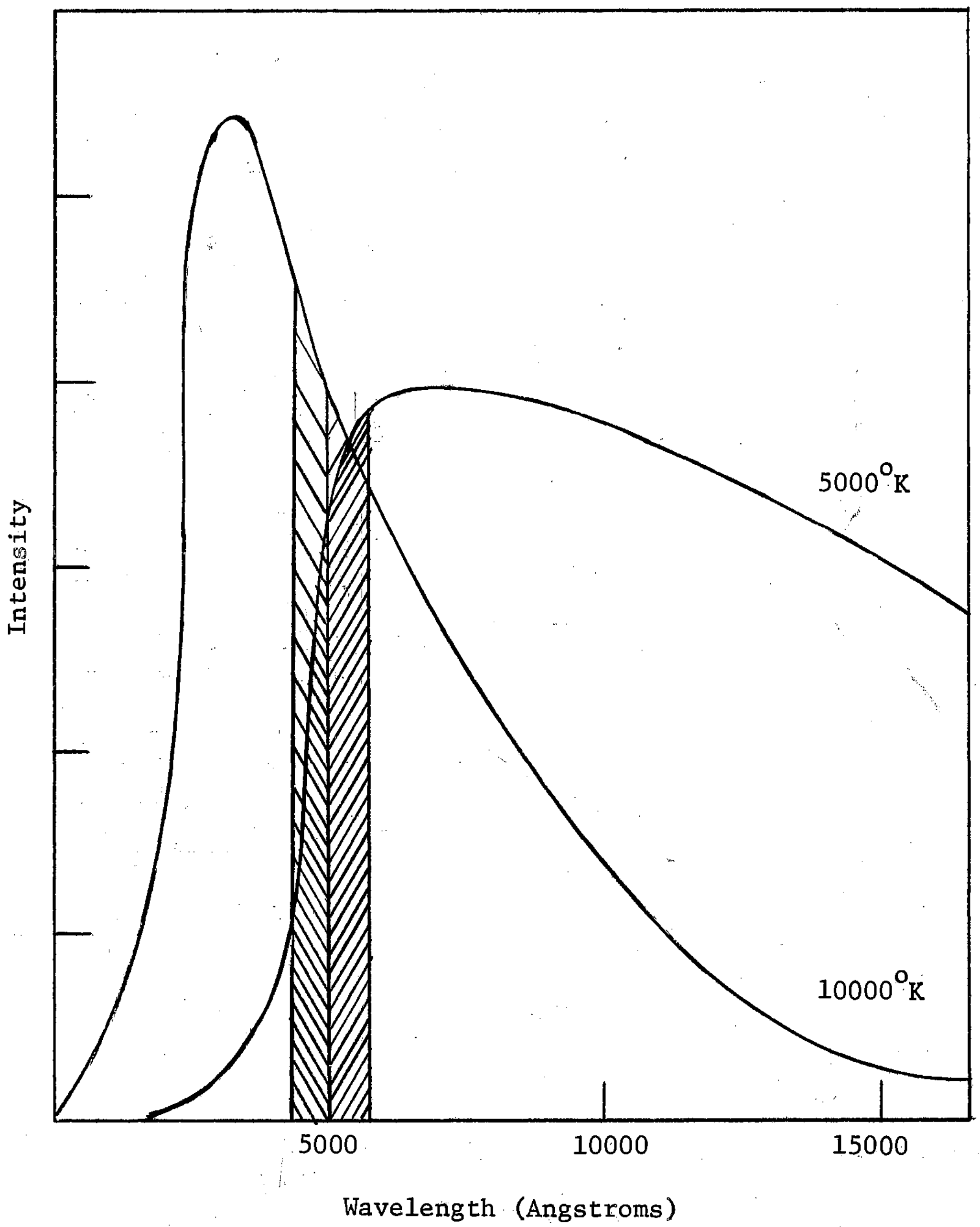

Figure 3. Photographic and Visual Spectral Sensitivity Regions on Planck Curves Corresponding to Stars of Different Temperature

color. Thus, the "problem" of a given star having different photographic and visual magnitudes was circumvented by defining a new quantity, <u>color index</u>, (CI) as the difference of the apparent photographic magnitude (m_{pg}) and the apparent visual magnitude (m_v).

$$CI = m_{pg} - m_v .$$

Parkhurst and Jordan (20, 21), working at the Yerkes Observatory during the years 1904-1908, determined stellar color indices as defined above. Using orthochromatic plates and a yellow filter, to measure a "visual" magnitude, these observers were the first to determine colors entirely by photographic methods.

Later work by Seares and others led to the development of additional photographic techniques for measuring color. With production of the panchromatic emulsion, which is sensitive to longer wavelengths, it became possible to match the spectral response of the eye by proper choice of filters and emulsion. Photovisual magnitudes, which compared closely with the older visual magnitudes, were then combined with photographic magnitudes to give more accurate color indices.

Color index, a quantity which is easily and precisely determined for a given star, is a good measure of the energy distribution in stellar radiation. This, in turn, leads to prediction of surface temperature and other parameters of astrophysical interest. Thus, color index is one of the most important "bits" of information carried by radiation quanta.

Photographic techniques developed during the first three decades of the twentieth century remain extremely valuable in the general field of astronomical photometry. Much of what was learned concerning the necessity of standardizing magnitude scales and the use of color index has been carried over to modern photoelectric work. One of the most obvious advantages of photography over photoelectric measures is economy of telescope time; i.e., up to millions of star images can be recorded on a good plate, and this is particularly helpful in the location of variable stars. However, the main disadvantage of the photographic plate is its non-linear response to varying quantities of radiant energy. The photoelectric effect, the baisis of photoelectric methods in astronomical photometry, is linear over a wide range of brightness. For this reason, photoelectric methods have been widely adopted, and astronomical photometry has in general come to mean photoelectric photometry.

Photoelectric Photometry

The photoelectric effect was first reported by Hertz (22) in 1887, having been observed during experimental verification of Maxwell's electromagnetic theory of light. During the following fifty years experimental and theoretical developments, culminating in the formulation of relativity and quantum mechanics, provided a plausible basis for what is now referred to as the photoelectric effect. When electromagnetic radiation strikes a metallic surface, it is possible for the energy associated with the radiation to be transferred to the metal. This transfer takes place in such a way that the conduction electrons in the metal are raised to higher energy levels and may, under proper conditions, be found outside the metallic surface. The importance of the photoelectric effect for astronomical photometry is based on its <u>linear</u> response to intensity changes. A change in the intensity of radiation by a factor R produces a change in the photocurrent by the same factor R. Hence, brightness measures employing photoelectric methods essentially involve detection and measurement of electric currents.

The earliest astronomical applications of photoelectric phenomena made use of photoconductive cells. G. M. Minchin (23, 24), in 1895, attached such a cell of his own design to a 24-inch reflector and obtained measurable results from Jupiter, Saturn, Vega, and other bright sources. A quadrant electrometer was used as a measuring device.

In 1906, Joel Stebbins (25) became interested in the possibility of using a selenium cell to detect and measure stellar radiation at the focus of a telescope. The development of photoelectric astronomy was, for more than fifty years from that time, inseparably linked to the work of Dr. Stebbins. His professional activity spanned well over half a century, and his last paper was written in collaboration with G. E. Kron, about two years before his death at the age of 87. Kron, who has done much to develop electronic instrumentation for use in photometry, well illustrates the tendency of Stebbins' associates to make major contributions in photoelectric work. In addition to Kron, others with whom Stebbins worked during his long and productive career include: F. C. Brown, who, in 1906, brought the selenium cell to Stebbins' attention and collaborated in subsequent experiments concerning lunar phases; Jacob Kunz, who was instrumental in adapting the photoemissive cell for stellar photometry during the years 1911-1913; C. M. Huffer, who has made many contributions in observational stellar photometry; and A. E. Whitford, who, in 1932, revolutionized experimental work by implementing an electronic (vacuum tube) amplifier to boost the signal from the photoelectric detector.

The experiments of Stebbins and Brown (26), during the years 1906-1907, represent the real beginning of photoelectric photometry. In the course of this research, which first involved lunar and later stellar observation, the sensitivity of the cell was continually improved by various methods. In particular, it was found that refrigeration with an ice pack improved the sensitivity markedly.

Following this preliminary work, Stebbins started a detailed photoelectric study of Algol, an eclipsing stellar system. In 1910, the reported results clearly showed a secondary minimum, previously undetected by photographic or visual methods (27).

During the years 1912-1913, while Stebbins was on sabbatical leave in Europe, Kunz and Schulz, working at the University of Illinois, developed a photometer employing a potassium hydride photoemissive cell. The results of stellar measurements with this arrangement were published in 1913 and represent the first "photoelectric cell" application in stellar astronomy (28). At the same time, very similar devices were being independently designed and installed by Guthnick (29) at Berlin and by Rosenberg and Meyer (30) at Tubingen. These three independent investigations reached essentially the same conclusion: the photoelectric cell, due to its higher sensitivity, was certain to replace the selenium cell in astronomical applications. The photoelectric cell, even from the start, outclassed all other forms of detectors from the viewpoint of accuracy and sensitivity.

From the time of these early experiments to the late 1940's the history of photoelectric photometers was one of constant improvement in both accuracy and sensitivity. Early improvements in the photocells themselves included, beginning in 1916, the use of fused quartz envelopes which not only provided better electrical insulation, but also gave higher ultraviolet transmission (25).

One of the most outstanding early improvements in current measuring techniques was the 1924 development of the Lindemann (31) electrometer. Although this instrument was not ultrasensitive, it was much more stable physically than previous types. In general, however, in spite of improved physical stability, the electrometer, at best a fragile device, was never well adapted to semi-portable operation on the telescope. Also, since these instruments were dependent on atmospheric drag for damping, it was not possible to evacuate the case, and the usual electrical difficulties arising from humid air often prevailed to make the operation unpredictable.

Most of these undesirable factors were eliminated by Whitford's vacuum tube amplifier, which was available for astronomical applications in 1932 (32). This instrument was used in conjunction with a sensitive galvanometer to measure the current output of the photocell. Although this type of equipment was more sensitive and much more convenient to use physically than the electrometer, signal to noise ratio imposed limitations at low levels of illumination, i.e., for faint stars. Attempts to improve the signal to noise ratio were centered on improvement of the cells themselves.

In the late 1930's P. Gorlich (33) developed a new class of photoelectric surfaces, the most sensitive of which was an alloy of antimony and cesium. About this same time, the technique of amplification by secondary emission experienced considerable development (34). Researchers at RCA and elsewhere began work on the production of high sensitivity photocells incorporating a secondary electron multiplier in the same tube with the photocathode. The resulting phototubes, photomultipliers, had very high sensitivity, and the RCA 1P21 had the highest quantum efficiency of any in this group.

Since their inception, photomultipliers have been applied extensively in the general field of radiation measurement. In 1946, G. E. Kron (35) published a very important paper on the application of photomultipliers in astronomical photometry. Kron found the 1P21 to be "many times superior to light sensitive units previously used for photometry in the blue region of the spectrum." In following years, the 1P21 was adopted by many photoelectric observers, including Johnson and Morgan (36) whose three color system is the standard for UBV photometry. The development and mass production of good photomultipliers, such as the 1P21, played a major role in the definition of standard photometric systems of sufficient precision for the purposes of modern astronomy.

Modern photoelectric techniques were developed concurrently with improvements in the instrumentation. Color index measurements were taken up by Guthnick and Prager (37) in 1916. The method involved observation both with and without a yellow filter. In effect, the spectral response of the detector was modulated by a broad band-pass filter, and this remains the general method used to obtain color measures.

Following these experiments, many observers were engaged in photoelectric color determinations. One of the more elaborate systems is that of Stebbins, Whitford, and Kron (38), which originally made use of a refrigerated cesium oxide cell and six filters. In the period from 1910 to 1950, a multitude of systems evolved, and as the number of systems increased, the necessity of defining one or more standard systems became evident. Whereas this had been virtually impossible for visual and photographic work, due to the non-linear nature of the detectors, the precision and reliability of photoelectric detectors made standardization quite feasible.

H. L. Johnson appears to have coordinated the movement toward standardization of photometric systems. Johnson's work, during the past twenty years, not only defined a standard system for UBV photometry but also serves as a model for the standardization of other multicolor systems.

In Chapter II of Basic Astronomical Data, Johnson (12) has carefully examined the practical basis underlying definition of a standard system. It is therein pointed out that useful data, useful in the sense that it provides information which can be interpreted to give physical characteristics of stars, can be obtained without a generally accepted standard system. In this case, however, it is necessary for each observer to accumulate sufficient data with his own system to provide a basis for comparing his interpretations to those of other observers. This procedure leads to repetitious observation of many bright standard stars. On the other hand, if all observations were referenced to a standard instrumental system, time that would otherwise be spent making routine observations of standard stars could be utilized for other measurements. This is the prime consideration which makes definition of a standard system desirable.

Johnson (12) identifies, on pages 221-222, four photometric systems, out of the principal photoelectric systems now in existence, which "will be used for virtually all the broadband photometry of the future." These systems are: the UBV system of Johnson and Morgan (36); the $(P,V)_E$ system of Eggen (39); the RI system of Kron and his collaborators (40, 41, 42); and the six-color photometry of Stebbins, Whitford, and Kron (38).

In his concluding paragraph, Johnson (12) presents an accurate and concise picture of present day photometry;

> During the past decade, the engineering problems of astronomical photometry have been carried to acceptable solutions. Satisfactory photometric systems of the required precision have been set up and tested. Photoelectric photometers of great sensitivity, efficiency, and convenience have been designed and constructed. Good methods of using photographic photometry in conjunction with photoelectric observations have been worked out. We are now ready, from these standpoints, to go ahead on large-scale photometric programs that will provide us with a great deal of information about the universe. It seems probable that the next decade will see our present methods and systems combined with modern computational methods, resulting in a veritable flood of accurate photometric data. The methods and procedures are available--they will be used.

Present day trends toward computer controlled facilities and in-line data processing leave little doubt as to the present and future accuracy of these predictions (43, 44).

CHAPTER III

DESIGN CONSIDERATIONS AND DESCRIPTION OF INSTRUMENTATION FOR A THREE COLOR PHOTOELECTRIC SYSTEM

Design of the Standard UBV System

The intended use of a photometric system determines, to a considerable extent, the location and bandwidth of the spectral regions to be observed. Moreover, significant restrictions on the choice of spectral regions and bandwidth are dictated by the color response of available detectors. Thus, the visual and blue regions of the International System were delimited by the spectral sensitivity of the eye and early photographic plates respectively.

In view of the large quantity of data which has been reduced on the basis of the International System, it is expedient to incorporate the blue and visual spectral regions of that system as part of a standard photoelectric system. Furthermore, if the system is to be applied to faint stars, as well as bright ones, the spectral regions of maximum sensitivity should be relatively broad. Finally, the addition of a third spectral region, i.e., ultraviolet, to the usual blue and visual greatly extends the discriminatory capabilities of the system.

On the basis of these considerations the UBV system was designed with pass bands approximately 1000 angstroms wide centered on about 5500, 4300, and 3500 angstroms. The system is homogeneous, since a single standard apparatus was used for observation of ten bright stars which serve as primary standards (36). Additional standard stars, including all spectral and luminosity classes and several clusters, have been observed to provide magnitudes and colors which, along with those of the primary standards, define the operational characteristics of the standard apparatus (45). The physical parameters, such as limits and shapes of the pass bands, which govern the operational characteristics of the standard apparatus are known by the exact specification of filters, detector, and other pertinent components of the instrumentation.

Experience with photoelectric methods has shown that while it is not possible to construct instrumentation which exactly duplicates the performance of the standard apparatus, a photometer assembled according to the standard specifications will permit linear, single-valued transformations to the standard system. Johnson (12) has stated specifications which should be matched to provide concise transformation to the system: a reflecting telescope with aluminized mirrors should be used with an RCA type 1P21 photomultiplier; yellow filter - Corning #3384, standard optical thickness; blue filter - Corning #5030, standard optical thickness, cemented to 2-mm Schott GG13; ultraviolet filter - Corning #9863, standard optical thickness; observations should be made approximately 7000 feet above sea level, and reduction procedures of Johnson and Morgan (36) should be followed.

General Description of a Photoelectric Photometer

Before presenting a detailed description of the Enid System, it is convenient to discuss a generalized model of a complete photoelectric photometer. In general, the instrumentation is composed of two interrelated sub-systems: (1) an optical system which collects and concentrates electromagnetic radiation which in turn produces a signal; (2) electronic circuitry which detects, amplifies, and displays the signal. The link between these two sub-systems is the photomultiplier, which serves as both detector and amplifier. Figure 4 points out most of the major optical components.

The telescope to which the photometer is attached concentrates light from the object under consideration to form a real image at the focal plane. The focal plane diaphragm is used to limit, as closely as possible, the light falling on the photomultiplier to that from the image; i.e., the diaphragm is used to cut out peripheral background. In general, the diaphragm is adjusted to the smallest aperture consistent with seeing conditions and stability of telescope mounting.

The filters, usually made of glass, are used to select the region of the photomultiplier response curve which will be used to detect and measure radiation. Placement of the filters in the optical path is determined by choosing the area to be illuminated on the filters. This, in turn, depends on the f-number of the telescope optical system.

The field lens (sometimes called a Fabry lens), which is made of fused quartz or silica to provide ultraviolet transmission to about 3000 angstroms, forms an image of the telescope objective, illuminated by the star under consideration, on the cathode of the photomultiplier. This tends to restrict the image to a fixed location on the photocathode, independent of small variations of focal plane image position within the diaphragm aperture due to guiding errors. Without this restriction, the image would wander over regions of variable sensitivity on the photocathode, thus producing spurious variations in measured brightness of the star. The position of the field lens relative to the focal

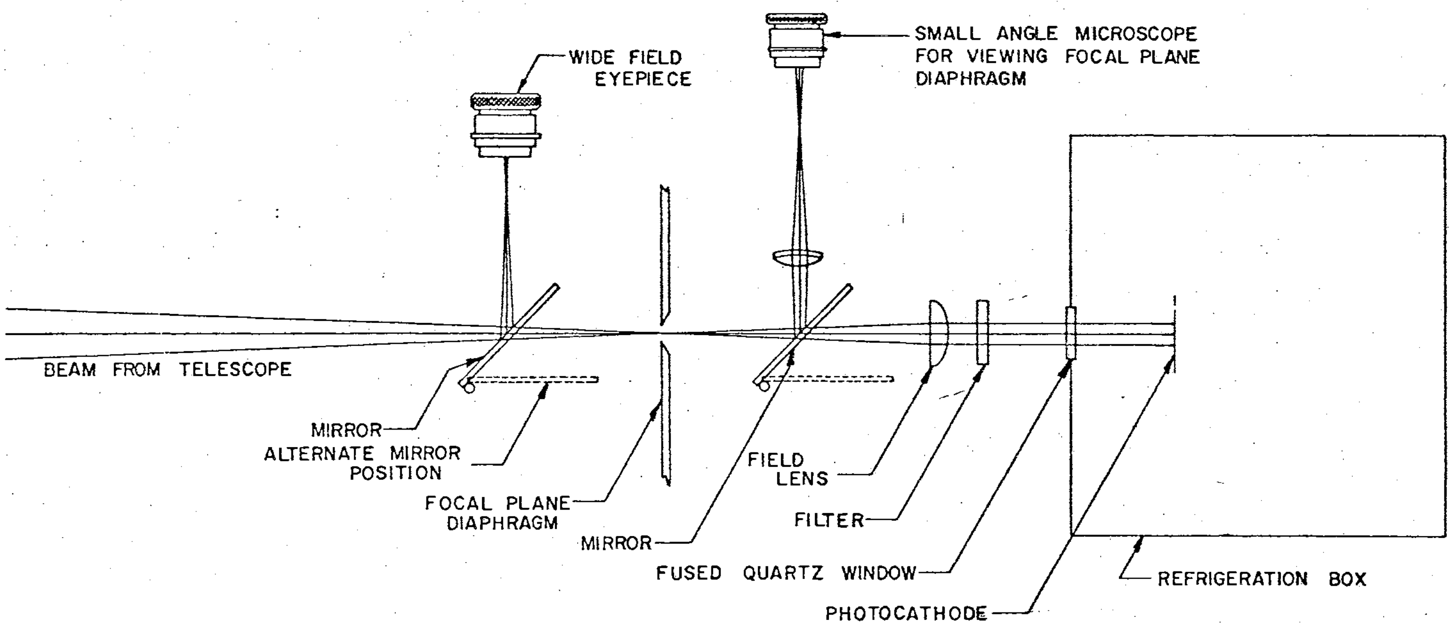

Figure 4. Cassegrain Focus Photometer

plane diaphragm is governed by the lens diameter and the f-number of the telescope optics.

The heart of any photometric system is the light detector--in this case the photomultiplier. The spectral response of the photocathode is a design consideration of prime importance, and the 1P21 is used for UBV systems to provide maximum sensitivity in the visual and near ultraviolet spectral regions.

An important property of all photocathodes is their temperature dependent color response. This is one reason why the photomultiplier is usually refrigerated--to provide a more nearly constant temperature and therefore a more stable color response. A lower temperature also reduces dark current. The refrigerant is usually dry ice, although liquid nitrogen is used in certain applications. The refrigeration box houses the detector in an air tight chamber to prevent condensation of atmospheric moisture. Appropriately placed heaters are used to keep the windows covering the light port into the box condensation free.

In addition to the optical components previously described, one or more auxiliary eyepiece assemblies are included to provide accurate aiming of the telescope at the object being studied. The wide angle assembly is used for finding and preliminary centering of the object. Final adjustment is made with the small angle microscope which provides a highly magnified view of the focal plane diaphragm.

In general, essential electronic circuitry includes, in addition to the photomultiplier, an amplifier, regulated power supplies for amplifier and photomultiplier, and display devices. The availability of highly linear d.c. amplifiers of sufficient stability has made them the most popular choice for astronomical photometry. Frequently, as a matter of convenience, commercial amplifiers are altered to provide gain control in steps of ½ magnitude. Also, sufficiently stable high voltage supplies are available commercially. The added expense and complexity involved with pulse counting techniques makes that approach feasible only for systems handling large volumes of data, or for work near the limiting magnitude of a given system.

Display may be accomplished simply by means of a panel meter equipped with a mirror scale to reduce reading errors due to parallax. Usually, in contemporary practice, the amplified signal is monitored by a time-base chart recorder, thus a continuous and permanent record of the observations is provided. Highly automated systems employing digital readout, punched tape output, and in line computing techniques are also in use.

The Enid System

The photometer was designed for use with the 8-inch Tinsley Model D, Cassegrain (Dall-Kirkham), f/16, telescope located at the High School Observatory in Enid, Oklahoma. The existing photometric system was built around the Photon Meter (#86407) and the Star Magnitude Meter Optical Attachment (#86408-2), both of which are manufactured by Cenco Instruments Corporation. The Photon Meter, which includes amplifier and high voltage power supplies, was not altered in any significant way. The Optical Attachment was salvaged to obtain the iris diaphragm. The main features of the photometer design include the following: dry ice refrigeration of the photomultiplier; fused quartz field lens; a convenient means of replacing damaged or otherwise inoperative filters; removal of flexure; small angle eyepiece assembly for viewing focal plane diaphragm. Design for the modifications was worked out by reference to the literature, and construction was carried out in the Physics-Chemistry Instrument Shop at Oklahoma State University (46, 47, 48, 49). Heathkit Servo Chart Recorder, Model EU-20A, was employed in conjunction with a panel meter for display.

Electronic Circuitry

The current detector, high voltage power supply for photomultiplier and power supply for the amplifier are all contained in the Photon Meter. Since a rather complete description of this unit is available in the manufacturer's literature, only a brief summary will be given here. The circuit diagram for the Photon Meter is shown in Figure 5.

Current, generated when electromagnetic radiation strikes the photocathode of the 1P21, is detected by a differential cathode follower. Current sensitivity is selected from nine ranges which vary from 10 microamperes to one nanoampere for full scale deflection. Meter display and 100 mv (full scale) monitor are available. High voltage may also be read on the meter. The photomultiplier power supply is continuously variable from -600 to -1500 volts at 3 ma, and it is regulated by a series tube and amplifier.

For astronomical work it is convenient to express current sensitivity and photocurrent in magnitudes rather than microamperes. The conversion is as follows:

$$m - n = 2.5 \log_{10} (l_n/l_m)$$

where m is the magnitude of the source which produces the <u>full scale deflection</u> l_m of the meter or recorder. For convenience, this expres-

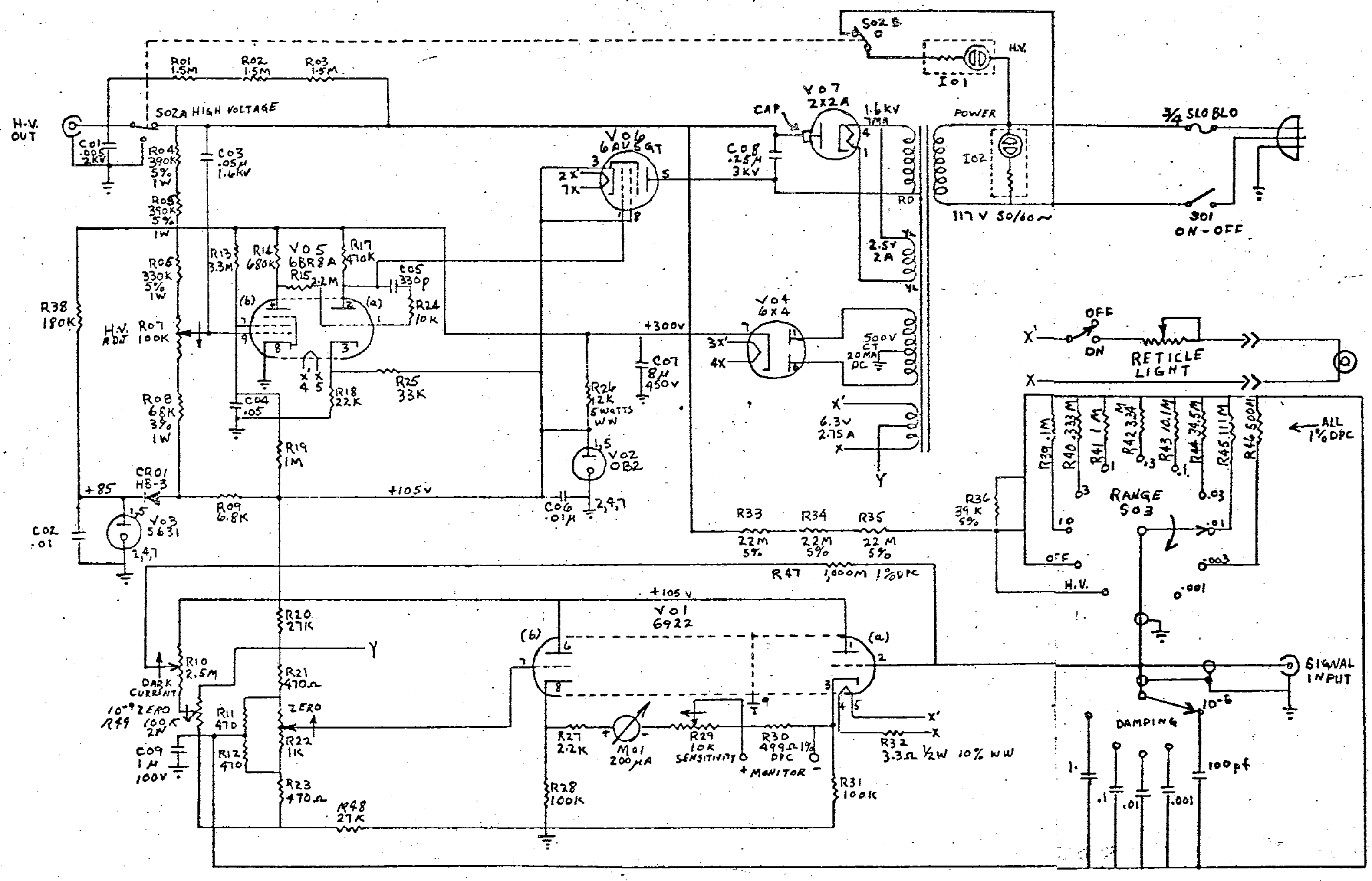

Figure 5. Photon Meter Schematic Diagram

sion is rewritten as follows:

$$n = S - 2.5 \log_{10} d_n \qquad (3\text{-}1)$$

where S is the sensitivity in magnitudes (corresponding to full scale deflection) and d_n is the deflection, expressed as a fraction of full scale, corresponding to a source of magnitude n. Using these relationships, current sensitivity for the various ranges of the Photon Meter may be expressed as in Table III. It is understood that the zero point is set arbitrarily by assigning a magnitude of 1.00 to full scale deflection on the least sensitive scale.

The socket for the 1P21 is wired according to Figure 6. Dynode resistors (R01 through R10) and capacitors C01 and C02 are wired directly to the socket which is enclosed in an air tight chamber to prevent condensation upon cooling. A vacuum feedthrough is used for the high voltage and signal leads. Ground connections are made to the photometer case.

The photomultiplier socket was carefully chosen to minimize leakage. It is necessary to use a socket made from mica-filled bakelite or ceramic, since ordinary bakelite will not in general provide sufficient insulation between the cathode (pin #11) and anode (pin #10) when high voltage is applied.

Electrostatic shielding and magnetic shielding are accomplished by applying the shielding material directly to the 1P21. Copper foil was wrapped tightly around the glass envelope, a rectangular aperture being left to admit light. Next, a layer of plastic electrical tape was applied to provide electrical insulation and mechanical support. The foil is connected to the photocathode by means of a thin wire soldered

TABLE III

PHOTON METER CURRENT SENSITIVITY

Range	Full Scale Deflection (Microamps)	Sensitivity (Magnitudes)
10.0	10.0	1.00
3.0	3.0	2.31
1.0	1.0	3.50
0.3	0.3	4.81
0.1	0.1	6.00
0.03	0.03	7.31
0.01	0.01	8.50
0.003	0.003	9.81
0.001	0.001	11.00

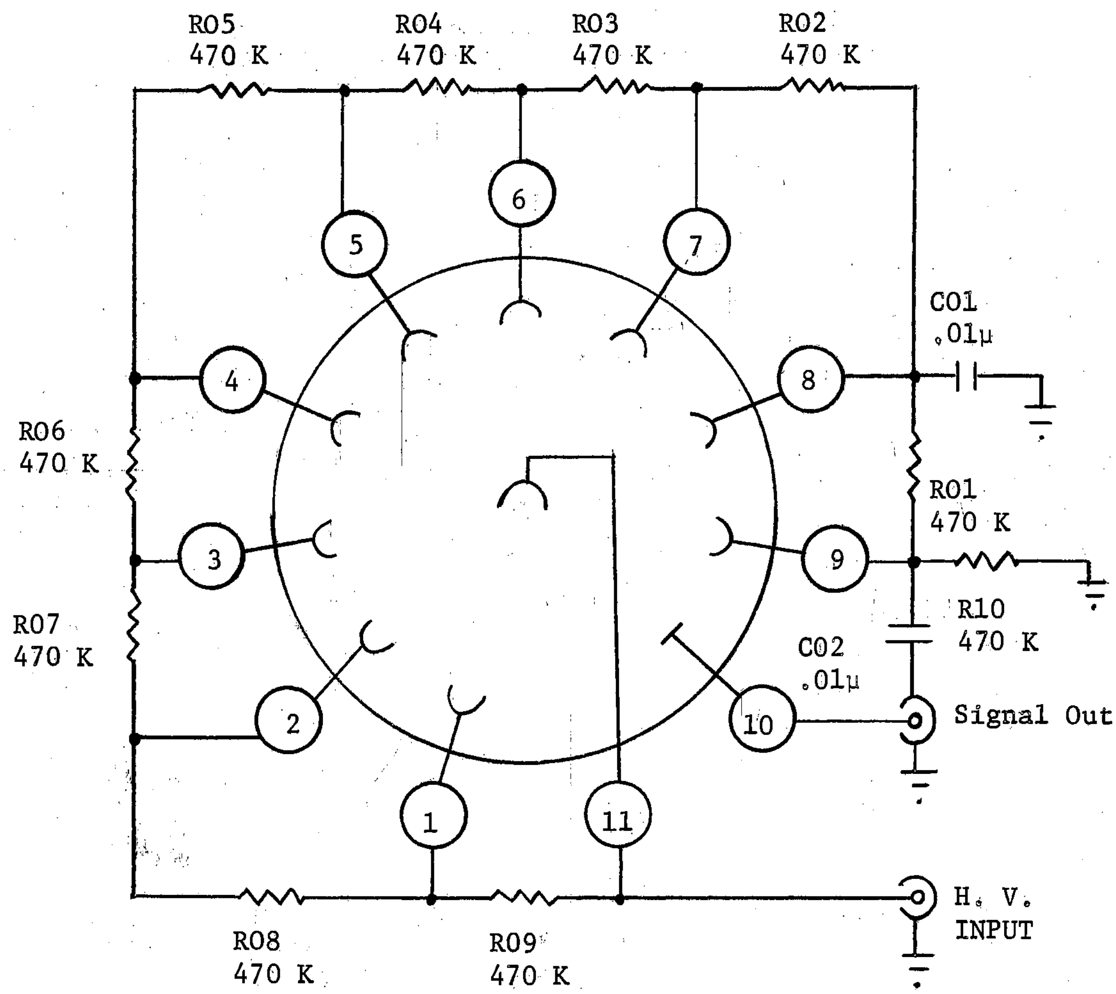

Figure 6. Detector Head Schematic

to pin #11 through a hole in the side of the tube base. The next layer is the magnetic shield and is composed of a .004 inch thickness of adhesive-backed Shieldmu 30. A final layer of plastic tape was added for further mechanical support. Figure 7 illustrates the tube socket, the mounting of the tube, and the photomultiplier.

The Optical System

Figure 8 shows placement of the major components of the optical system. The eyepiece assembly, designed for viewing the diaphragm, consists of a prism, two achromats of focal length 57 mm, and a conventional eyepiece. The achromat closest to the diaphragm is positioned so that it collimates light coming from the plane of the diaphragm, and the second achromat focuses this parallel light a convenient distance away from the central axis of the photometer. The diaphragm may be illuminated by a grain of wheat bulb, and after final adjustments have been made the prism is removed from the light path by sliding the entire assembly away from the central axis, thus allowing light from the focal plane image of the star to traverse filters and field lens before striking the photocathode.

Four different filters are provided, each of these being either a single type or a combination of two types of Schott Optical Glass. Mineral oil was used to bind the composite filters. The following glass types and thicknesses were used: ultraviolet (U) - UG2, 2 mm; blue (B) GG13, 2 mm plus BG12, 1 mm; visual (V) - GG14, 2 mm. In addition to these standard filters, a composite filter consisting of UG2 and RG1, 2 mm and 1 mm respectively, is provided for use in determining red leak of the ultraviolet filter. All filters are one inch in diameter and

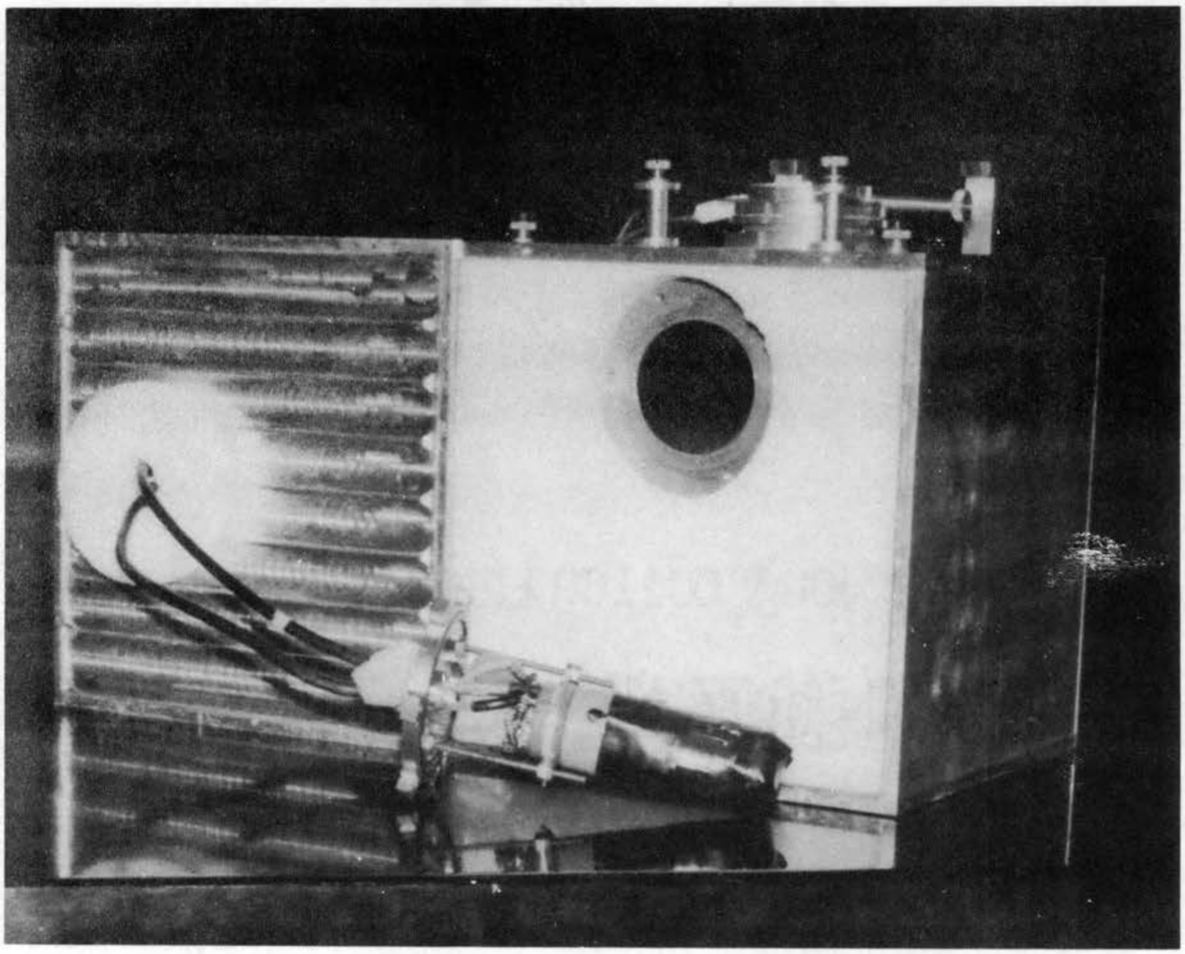

Figure 7. Tube Socket Assembly and Photomultiplier Chamber

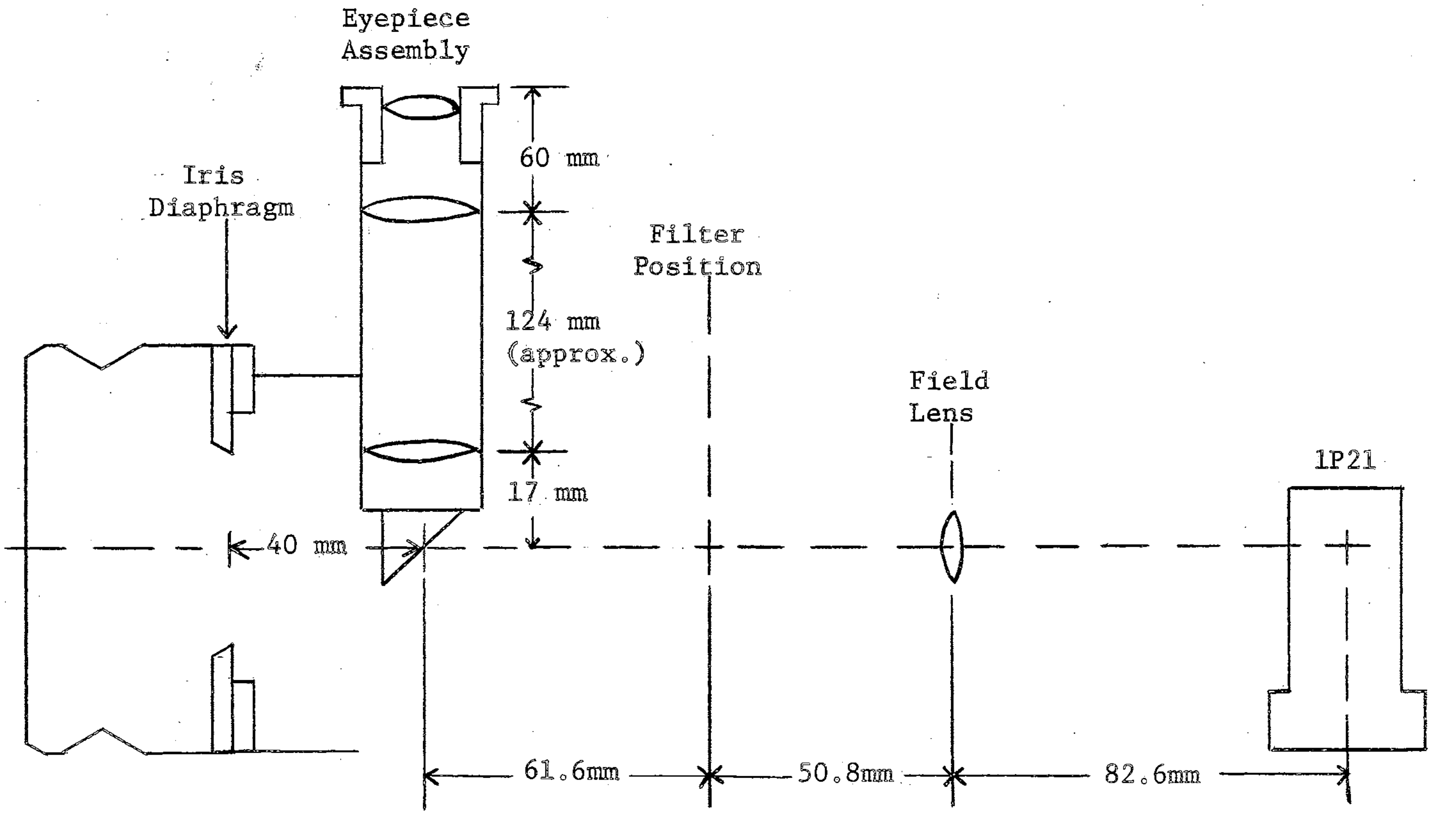

Figure 8. Optical System

have an aperture of 3/4 inch when mounted.

The filters are placed four inches (101.6 mm) from the focal plane diaphragm. Since the focal ratio of the telescope is f/16, the illuminated area on the filter at this position is ¼ inch in diameter.

The field lens, which is made of fused quartz, has a focal length of three inches and a diameter of ½ inch. Since the telescope objective is effectively 128 inches away, its image will be very close to the principal focus of the field lens. Since the field lens is situated relatively close to the focal plane of the telescope, the ratio of field image spot size to telescope objective diameter is essentially the same as the ratio of field lens focal length to objective focal length. From this it follows that the diameter of the spot image on the photocathode is 3/16 inches.

The region of best collection on the photocathode of the 1P21 lies between 0.10 and 0.20 inches in front of the central axis of the tube. Accordingly, the position of the field lens relative to the central axis of the tube is set at about 3.25 inches, and provision is made for fine adjustment of this dimension.

The position of the field lens relative to the diaphragm is chosen to accomodate the largest diaphragm opening plus the additional fanning out of the divergent bundle of rays. Location of the lens six inches from the diaphragm allows for a beam diameter of 3/8 inch at the lens.

Mechanical Design

Although choice and proper positioning of suitable optical and electronic components are necessary considerations in photometer design, mechanical stability is of equal importance. In particular, flexure cannot be tolerated. Furthermore, mechanical design presents unique problems when the system is designed for a small telescope.

Figure 9 illustrates the first design employed. This model was not sufficiently rigid to provide freedom from flexure. Also, the mass center of the photometer was so far from the declination axis of the telescope that conventional methods of balancing the additional load were not feasible. It was found that the photometer could be independently suspended from dome superstructure in such a way as to reduce the amount of additional counterweights required; however, this scheme proved unsuccessful due to its interference with the telescope drive mechanism.

The preliminary design was modified to move the mass center closer to the declination axis, to reduce the total weight, and to provide adequate bracing to minimize flexure. In order to meet these requirements it was necessary to delete the rack and pinion focusing device and the wide angle eyepiece. The aluminum box which houses the refrigeration chamber was machined to get rid of excess weight. Bracing was designed to place most of the load of the photometer on the mounting saddle of the telescope, thus avoiding misalignment of the primary mirror cell. The resulting distribution of weight made possible a net zero torque condition about both polar and declination axes so that the telescope drive unit is not significantly taxed beyond the normal load for which it was designed.

The photometer is mechanically separable into the two subassemblies shown in Figure 10 and Figure 11. Figure 12 and Figure 13 show the assembled photometer. Figure 14 illustrates installation of the photometer and its counterweights on the telescope. Figure 15 shows

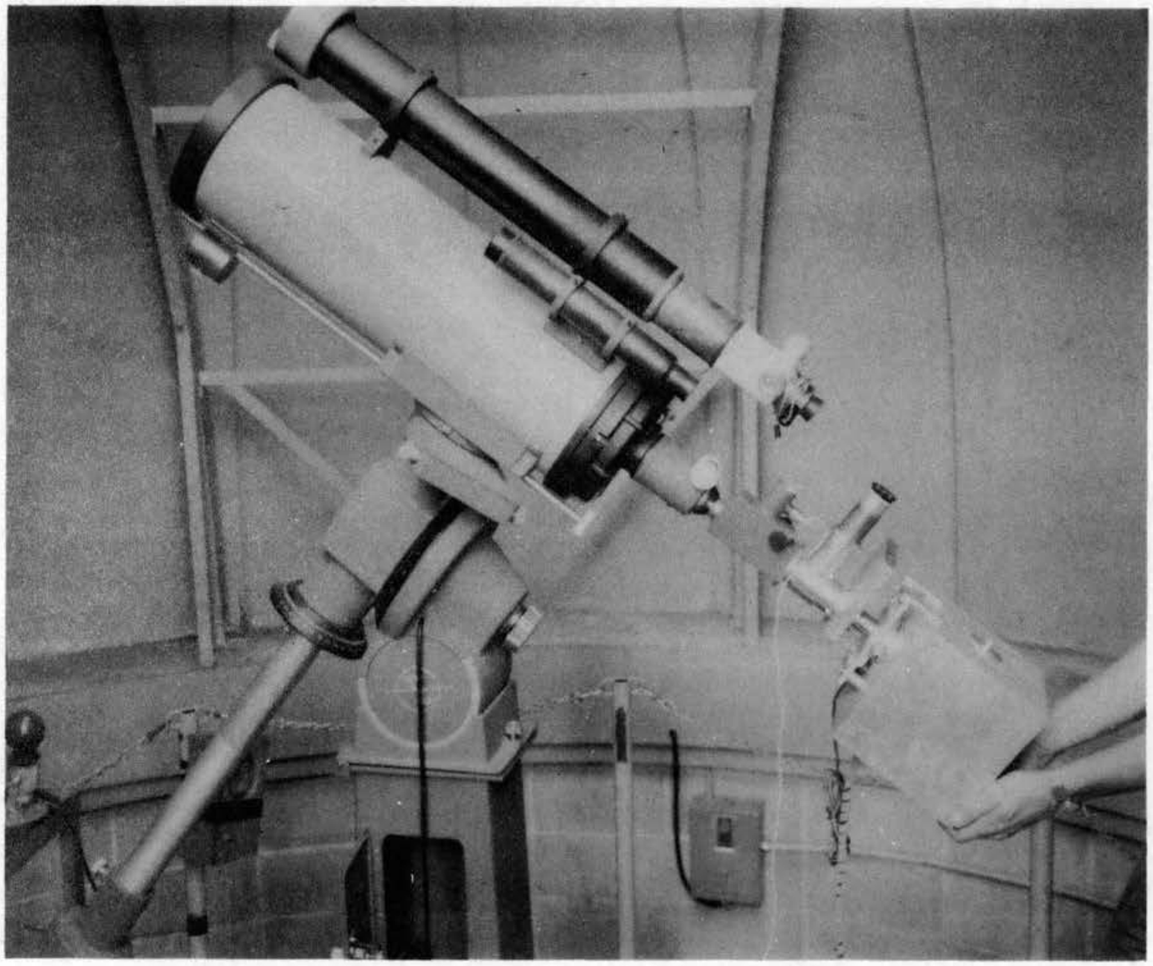

Figure 9. Preliminary Photometer Design

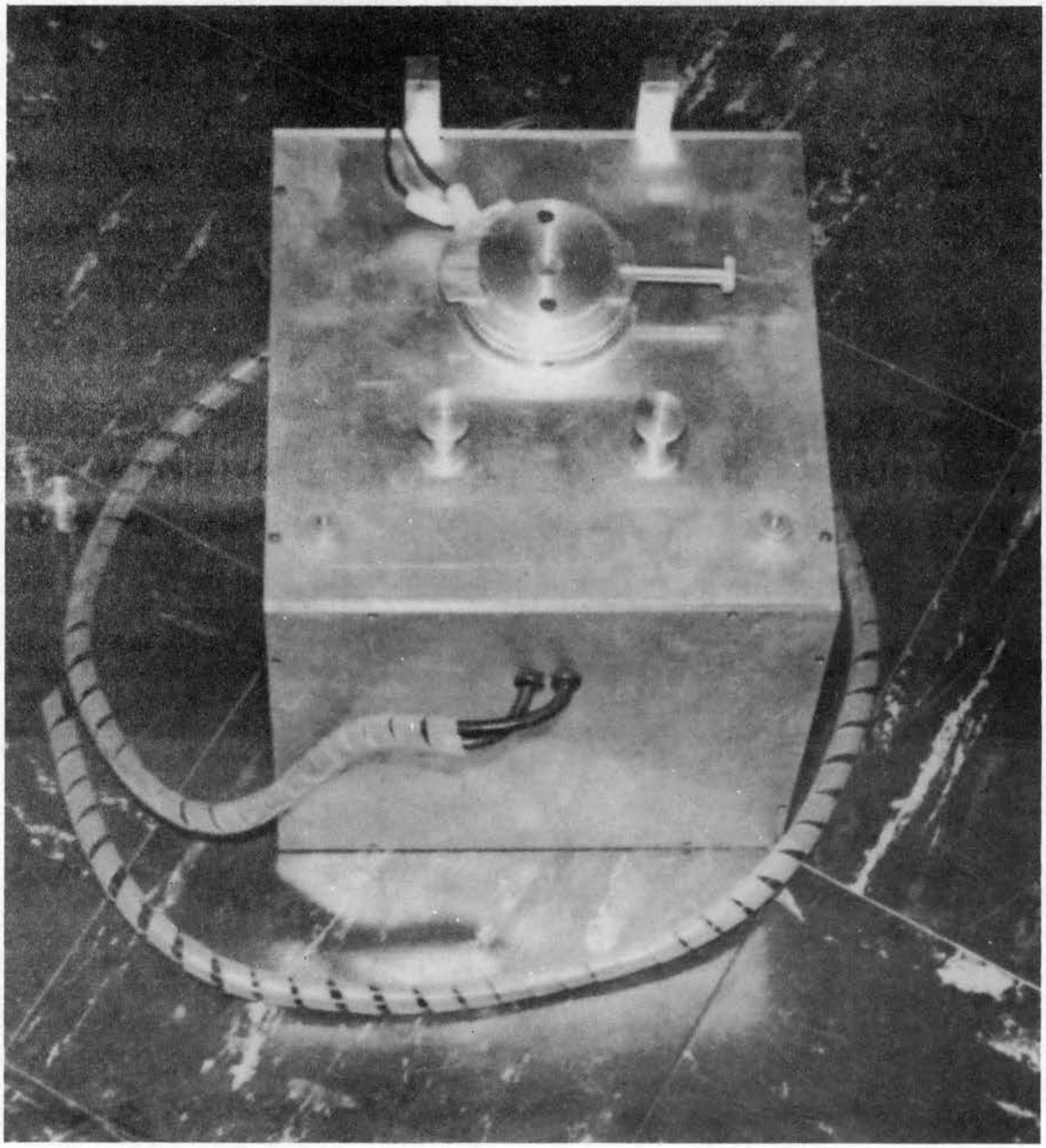

Figure 10. Refrigeration Box Subassembly

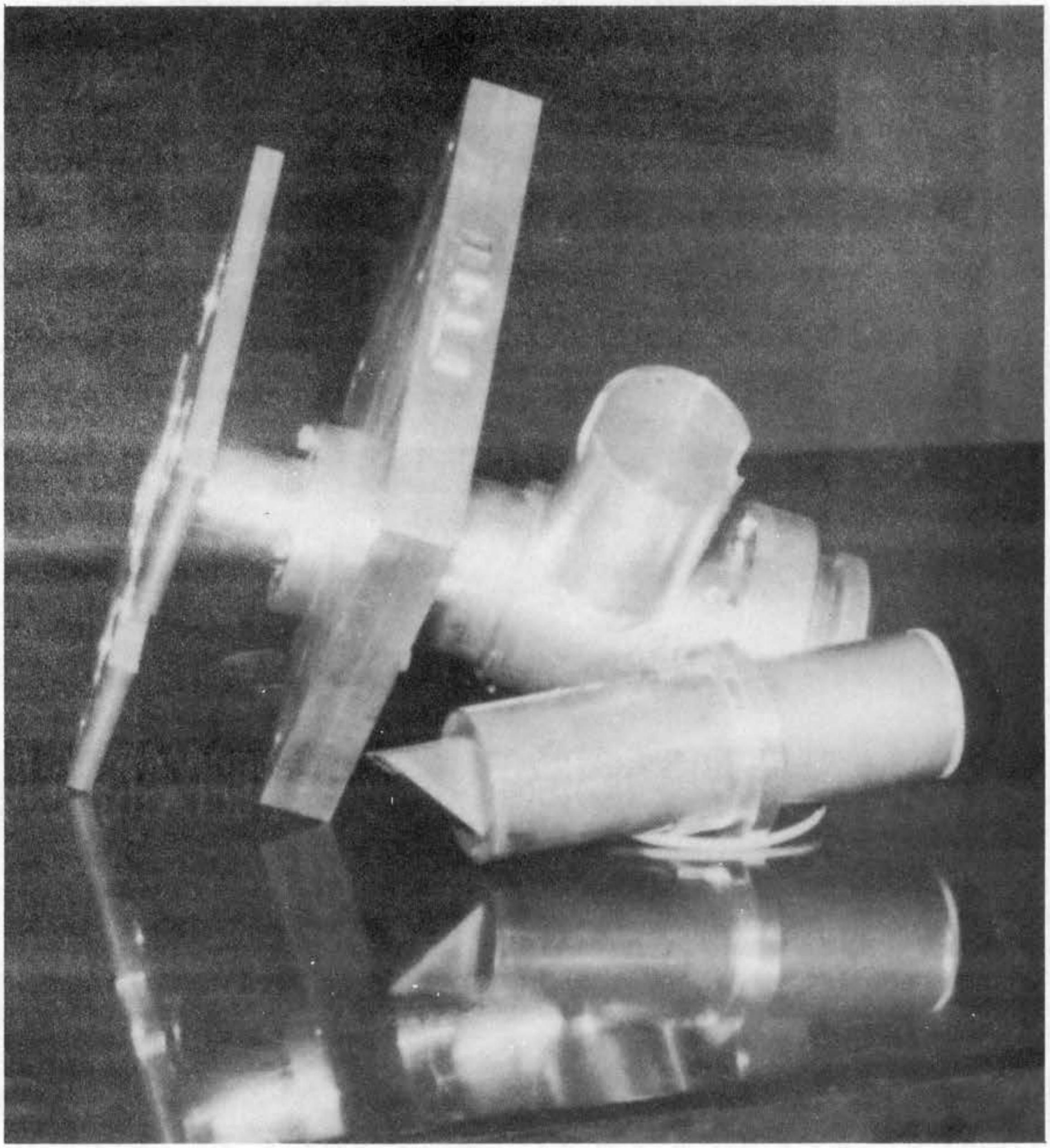

Figure 11. Optical Subassembly

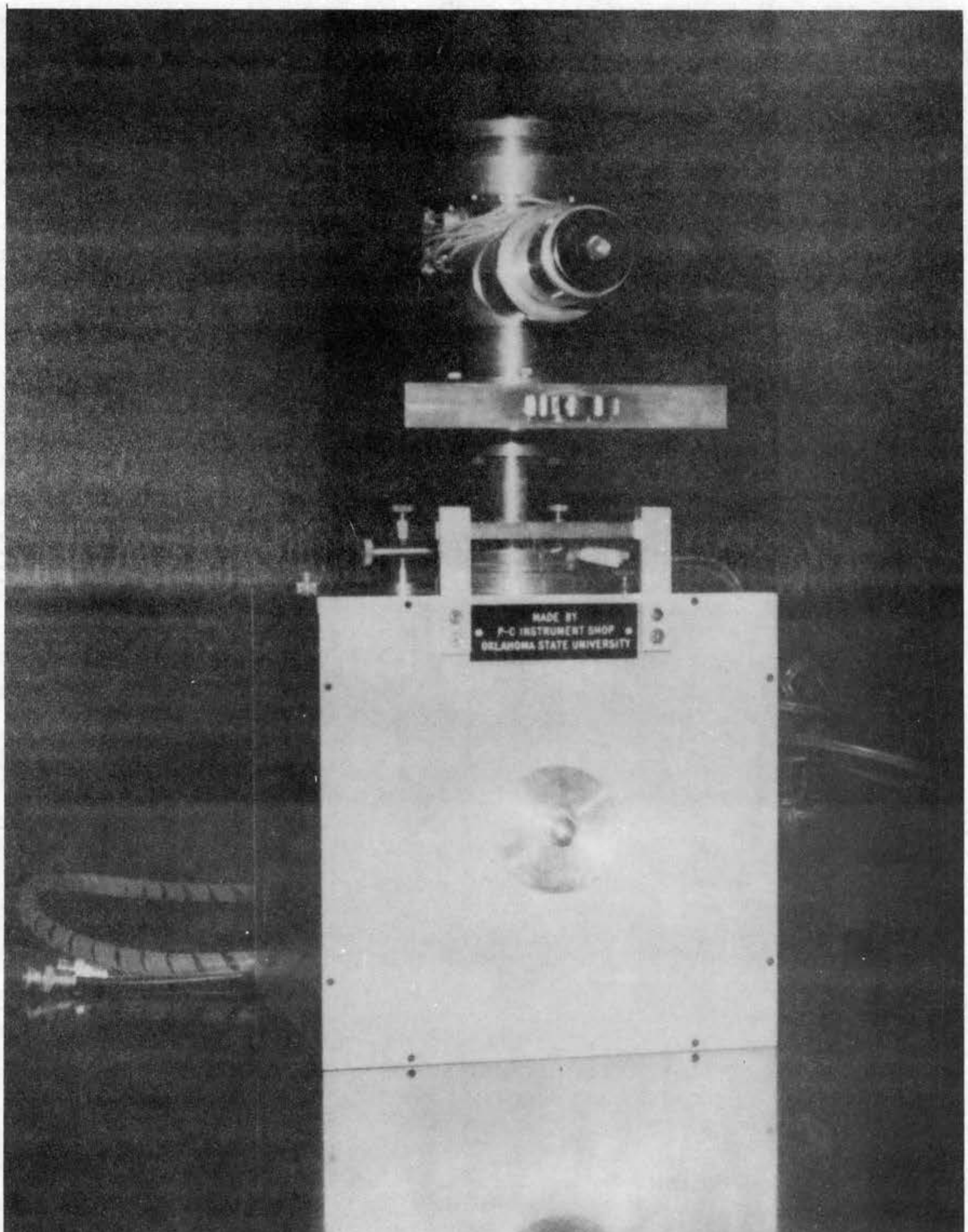

Figure 12. Photometer - Front View

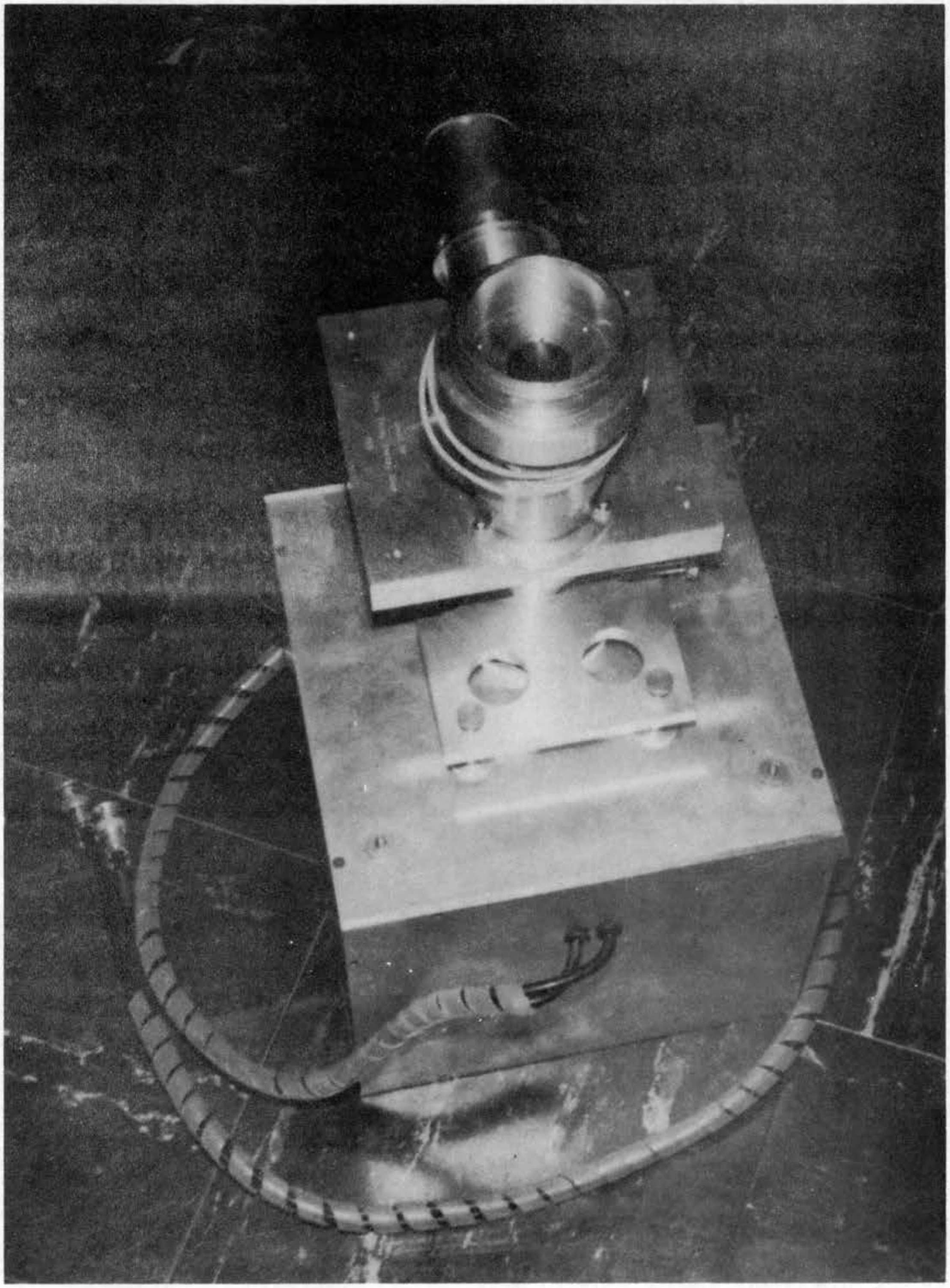

Figure 13. Photometer - Top View

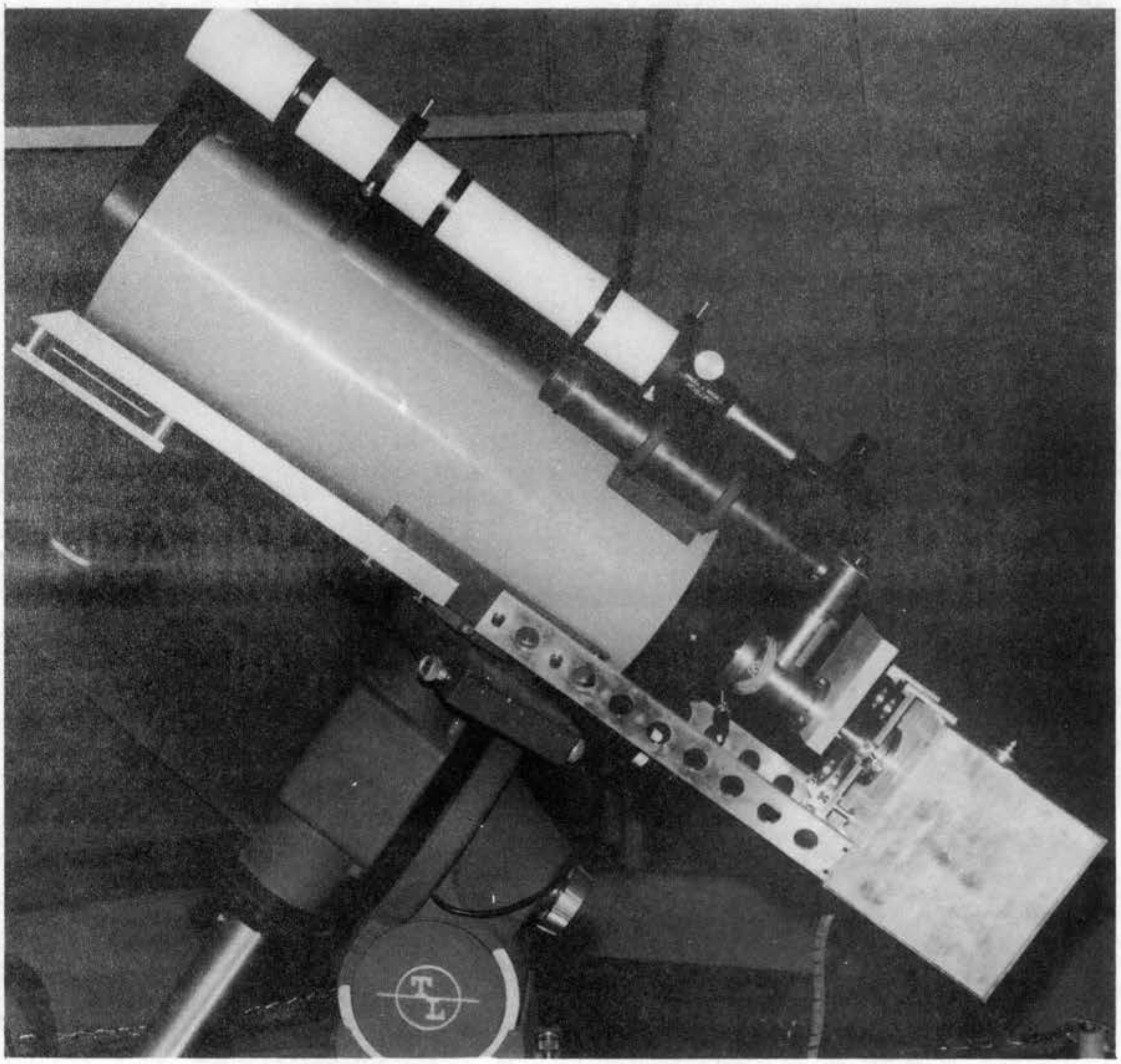

Figure 14. Photometer Installation

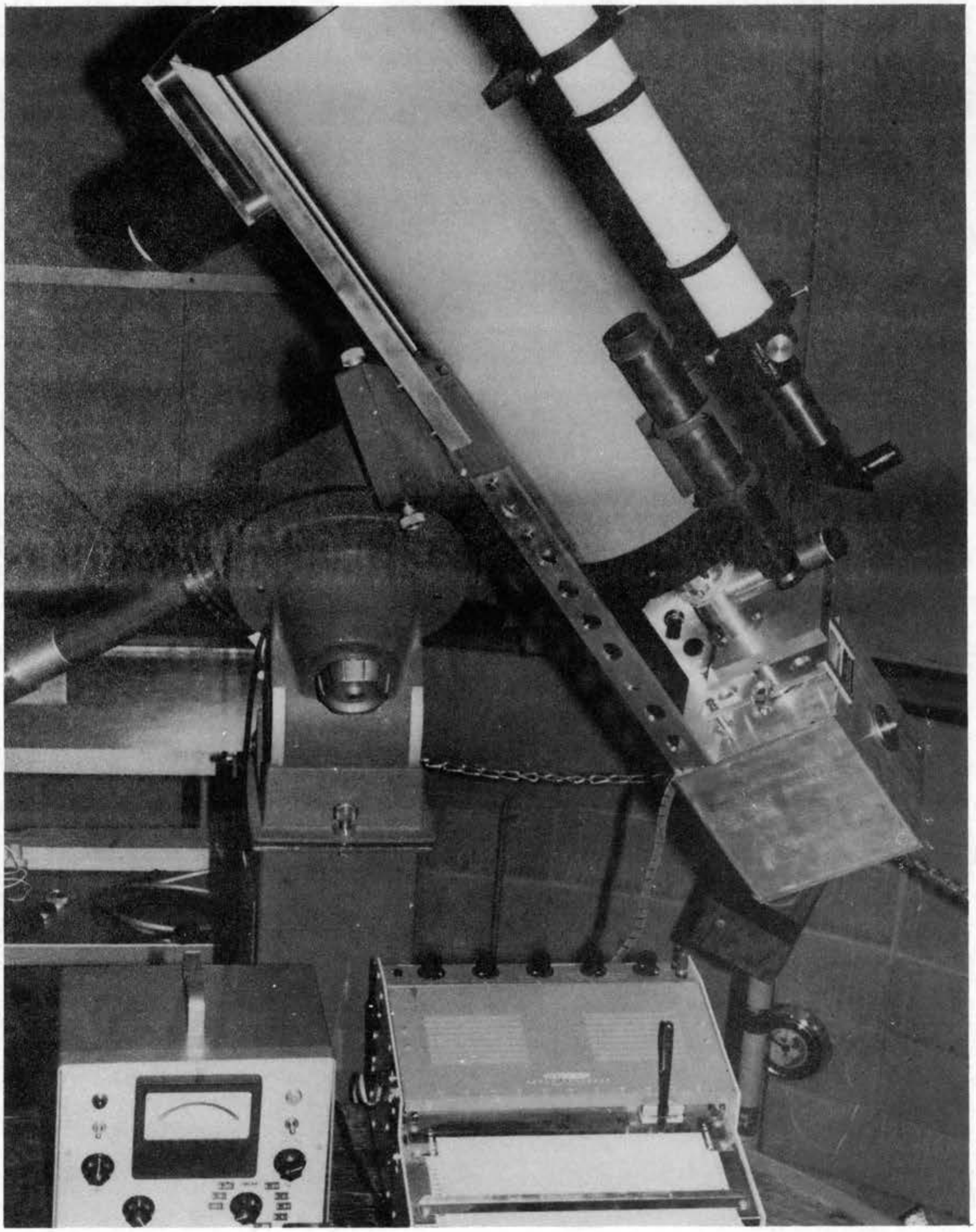

Figure 15. Enid Instrumentation

the telescope, photometer, amplifier, and recorder which comprise the Enid System.

The aluminum refrigeration box (Figure 10) houses the chamber for refrigerant and the photomultiplier chamber. The only physical connections between these inner chambers and the box, other than cables entering the photomultiplier chamber through the bottom of the box, are the refrigerant intake port, located in the top of the box, and the port for entry of light, located in the front of the box. Each of these ports is constructed of .005 inch (thick) stainless steel tubing. Reservoir and photomultiplier chamber are thermally insulated from the outer box by styrofoam. The reservoir will hold approximately five pounds of dry ice; however, experience shows 3 to 3½ pounds sufficient for a minimum of eight hours observation.

Access to the photomultiplier chamber is from the bottom. In Figure 7, the base plate which supports the tube socket assembly has been removed to expose the interior of the chamber. This chamber is rendered air tight by means of O-ring seals: one on the base plate and another on the quartz window where light enters. The vacuum feedthrough in the base plate provides electrical connections to the socket assembly.

A heater, used for keeping the quartz window free from water vapor, is a 16-inch length of 4.25 ohm/foot Nichrome wire. The heater coil is positioned immediately behind the dark slide (Figure 12), and it is joined to copper leads (zip cord) by crimped brass tubing. The junctions are insulated with asbestos held in place by teflon tubing. The heater is powered by a toy train transformer, and the maximum obtainable power is about 20 watts.

The other major subassembly (Figure 11) houses the field lens, filters, diaphragm, and diaphragm viewing assembly. The field lens is mounted in a threaded brass cell, and it should be positioned about 0.1 inch from the surface which fits flush against the dark slide face plate when the instrument is fully assembled. This is easily accomplished using the special tool provided.

The filter box contains a wheel in which four filters and a clear aperture are mounted. The filters are positioned in the light path by precision detents, and a color dot on the exposed edge of the wheel corresponds to the filter in the light path according to the following scheme:

Color Dot	Filter
Black	Ultraviolet
Blue	Blue
Yellow	Visual
Red	U-Red Leak
White	Clear Aperture

Access to the filters for cleaning or replacement is provided by a small cover plate.

Spectral Response and Operating Procedures

For the purpose of preliminary comparison of the completed instrument with both the original design and the standard instrumentation, spectral response was investigated in the range 3000 to 6000 angstroms. A source of constant radiant flux at all wavelengths in this range was provided by the monochrometer of the Beckman DK-1 spectrophotometer which is operated jointly by the Chemistry and Physics Departments at Oklahoma State University.

The specific procedures followed in this study, along with suggested operating procedures in normal applications have been stated elsewhere (50). The results of this study show the pass bands to be essentially those of the standard instrumentation (51). The larger, sharper response and the insignificant dark current at dry ice temperature makes this the optimum mode of operation. Red leak of the ultraviolet filter appeared negligible, and, as expected, the addition of the quartz window reduced the magnitude of the response at all wavelengths, compared to that of the original apparatus.

CHAPTER IV

TRANSFORMATION EQUATIONS FOR THE UBV SYSTEM

The reduction of observations involves correction for atmospheric extinction and transformation of the extinction corrected natural magnitudes and colors to the standard system. The topic of this chapter is the development of transformation equations which can be used for extinction corrections and transformation to the standard system. Methods for evaluation of extinction coefficients and constants in the transformation equations will also be discussed.

Atmospheric Extinction

Considering an element of absorbing material of thickness Δx, the change in intensity, ΔI, of radiation having intensity I traversing Δx is

$$\Delta I = - I \gamma \Delta x .$$

In the limit, as Δx approaches zero, the above expression becomes

$$dI = - I \gamma dx .$$

Integration over a path of length x gives

$$\ell n\, I = \ell n I_o - \gamma x,$$

$$\log I = \log I_o - \gamma_1 x,$$

$$\log (I/I_o) = -\gamma_1 x,$$

$$2.5 \log (I/I_o) = -2.5\ \gamma_1 x .$$

This can be written in terms of magnitude by use of Equation (3-1).

$$m_o - m = -2.5\ \gamma_1 x , \qquad (4\text{-}1)$$

where m_o is the original apparent magnitude and m is apparent magnitude after the radiation has passed through a length x of absorbing material. Combining constants, Equation (4-1) can be written as follows

$$m_o = m - kX, \qquad (4\text{-}2)$$

where X is measured in units of air mass at the observer's zenith.

The numerical value of X is determined by the position of the star relative to the observer's zenith. For a star at zenith, X=1.000, and X increases as zenith distance increases. To a good approximation, X is given by the secant of the zenith distance (z). This holds well up to z = 60°, where the inaccuracy in the approximation is 0.005 air mass. For larger values of z, the following expression gives a more accurate approximation to air mass (52):

$$X = \sec z - 0.0018167 (\sec z - 1) - 0.002875 (\sec z - 1)^2 - 0.0008083 (\sec z - 1)^3.$$

The numerical value of sec z is determined for any observation by the relationship

$$\sec z = (\sin \phi \sin \delta + \cos \phi \cos \delta \cos h)^{-1}$$

where ϕ is the observer's latitude, δ is the declination of the star, and h is the hour angle of the star. Stellar position coordinates are defined in Figure 16.

Due to certain selective mechanisms, including molecular absorption bands and molecular scattering, light which passes through the atmosphere is not only diminished in general, but is also reddened; i.e., shorter wavelengths are scattered or attenuated more strongly than the longer ones. Hence, each wavelength has a different absorption coefficient k_c. Writing out Equation (4-2) for blue (B), visual (V), and ultraviolet (U) gives the following:

$$(m_o)_B = m_B - k_B X,$$

$$(m_o)_V = m_V - k_V X,$$

$$(m_o)_U = m_U - k_U X.$$

From these three equations, the following are developed:

$$\begin{aligned} (m_o)_B - (m_o)_V &= m_B - m_V - (k_B - k_V)\, X, \\ (m_o)_U - (m_o)_B &= m_U - m_B - (k_U - k_B)\, X. \end{aligned} \qquad (4\text{-}3)$$

From the definition of color index, blue magnitude minus visual magnitude, it follows that:

$(m_o)_B - (m_o)_V \equiv (C_o)_{BV}$ (color index outside the atmosphere);

$m_B - m_V \equiv C_{BV}$ (color index at observer's position);

$k_B - k_V \equiv k_{BV}$ (extinction coefficient for color index).

LEGEND

γ:	Vernal Equinox	h:	Hour Angle
α:	Right Ascension	Z:	Zenith Distance
δ:	Declination	ϕ:	Observer's Latitude
θ:	Sidereal Time	★:	Star

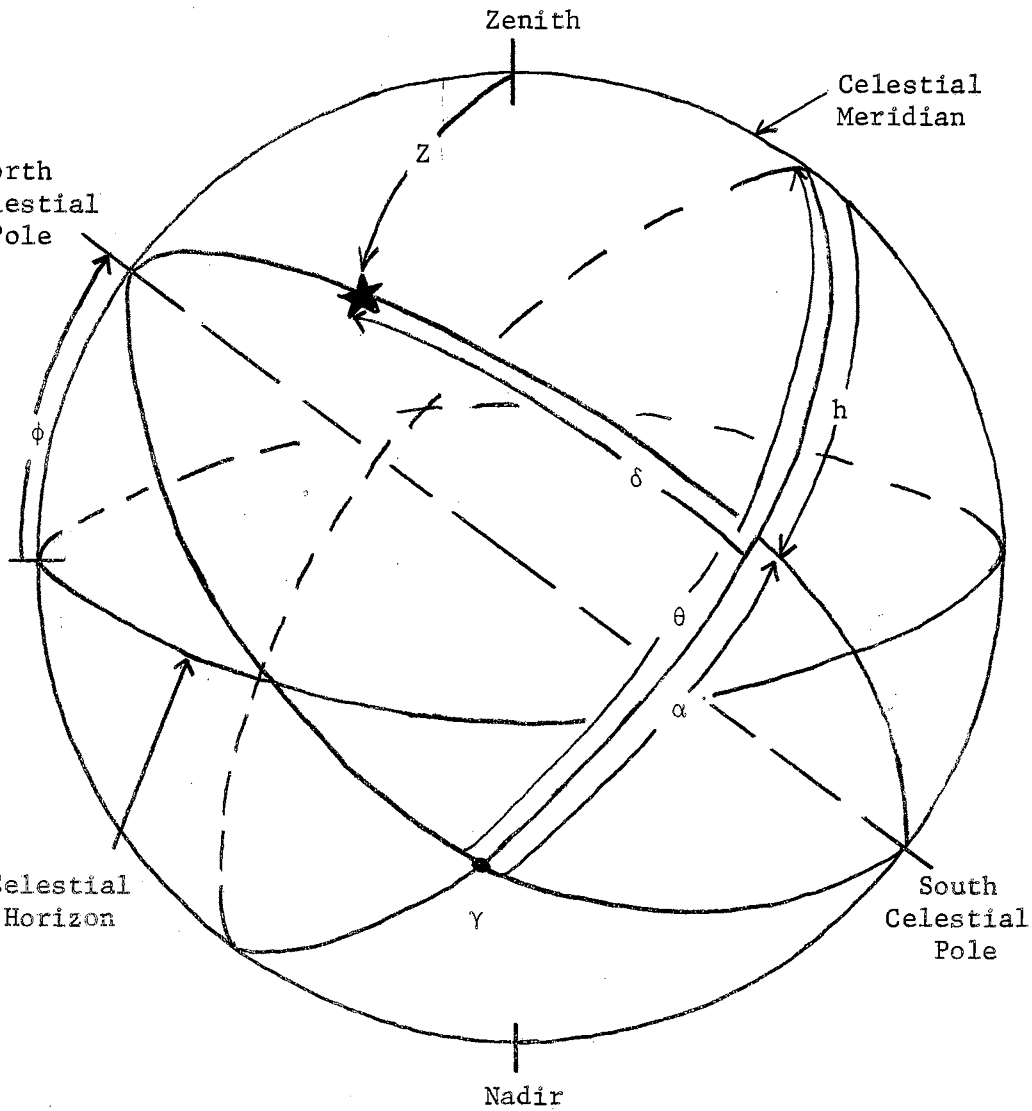

Figure 16. Stellar Position Coordinates

Thus, the first of Equations (4-3) may be written

$$(C_o)_{BV} = C_{BV} - k_{BV} X .$$

Similarly, for the U - B color index:

$$(C_o)_{UB} = C_{UB} - k_{UB} X ,$$

or, in general:

$$C_o = C - k_c X . \qquad (4\text{-}4)$$

Since the energy is not monochromatic in the photometric bands used, the measured extinction coefficients (k, k_c) will, in general, be some function of the color index of the star being observed (52). According to Hardie (7), it is usually possible, for the cases of interest here, to express extinction coefficients as a linear function of color index.

For the magnitude coefficient

$$k = k' + k'' C, \qquad (4\text{-}5)$$

where C = color index uncorrected for extinction; k' = magnitude extinction coefficient for star of zero color index; k'' = increment in magnitude extinction coefficient for star of color index C = 1.00.

Similarly, for the color coefficient

$$k_c = k'_c + k''_c C, \qquad (4\text{-}6)$$

where C is the uncorrected color index, k'_c = color extinction coefficient for star of zero color index, and k''_c = increment in color extinction coefficient for star of color index C = 1.00.

The quantities k' and k'_c are hereby defined as <u>principal coefficients</u>, while k'' and k''_c are defined to be <u>second order coefficients</u>. The use of the linear formulation above (Equations (4-5) and (4-6)), with the inclusion of second order coefficients, is justified on the grounds that present methods do not permit measurement of higher order terms.

The following expressions result from combining Equation (4-2) and Equation (4-4) with Equation (4-5) and Equation (4-6):

$$m_o = m - k''CX; \tag{4-7}$$

$$C_o = C\,(1 - k''_c X) - k'_c\, X. \tag{4-8}$$

By use of appropriate techniques, to be discussed in another section, the extinction coefficients can be measured experimentally. Thus, C_o and m_o may be determined from observed values of C and m.

Magnitude and Color Transformations

As pointed out previously, natural magnitudes and colors determined in systems of medium bandwidth photometry depend on the particular bands chosen in setting up the natural system. In order to meaningfully compare results with those of other systems, it is convenient to transform natural colors and magnitudes to standard values. Hence, the problem of relating measures made in one system to those made in another system is now taken up.

Hardie (7) has shown in paragraph 3.1 that if the stars are considered to be ideal black body radiators, then for a given star, the color index C_1 (measured in system 1) is related to the color index C_2 (measured in system 2) by a simple linear relationship, provided high temperatures and long wavelengths are avoided. Under these conditions, the relationship between C_1 and C_2 may be written in the form:

$$C_2 = \mu C_1 + \zeta_c . \qquad (4\text{-}9)$$

Real stars definiately do not radiate strictly as black bodies, the departures from black body behavior being caused by certain absorption features. Hence, simple linear transformations such as Equation (4-9) must be used with caution. Nevertheless, if certain conditions are met, the error involved in the use of Equation (4-9) and other equations developed from it, will not be significant, compared to experimental error, using present methods. Hardie (7) emphasizes the following three stipulations: the color systems must be closely matched; major spectral discontinuities, such as the Balmer discontinuity, must be excluded from the pass bands; stars of widely differing character (spectral class and luminosity class) should not be expected to fit a single set of transformation equations.

Assuming the validity of the linear theory outlined above, the following transformation is used to relate magnitudes measured in system 1 to those measured in system 2 for a given star:

$$m_2 = m_1 + \varepsilon C_1 + \zeta_m . \qquad (4\text{-}10)$$

Empirical determination of the scale factors, ε and μ, and the zero point constants ζ_m and ζ_c is accomplished by a sufficient number of common observations in the two systems. Specific methods will be discussed in a following section of this chapter.

Having set forth the limits of applicability of the linear theory described above, the next problem to be considered is reduction of raw data to standard magnitudes and colors. It is assumed that the natural system is designed to permit the use of linear transformations of the form (4-9) and (4-10).

The raw data which result from photoelectric observations are usually deflections of a meter or recorder pen. Writing out Equation (3-1) for the three colors of the UBV system gives observed magnitudes corresponding to deflections (d) which have been corrected for sky background and color leaks in the pass bands:

$$\begin{aligned} u &= S_u - 2.5 \log d_u, \\ b &= S_b - 2.5 \log d_b, \\ v &= S_v - 2.5 \log d_v. \end{aligned} \qquad (4\text{-}11)$$

The corresponding color indices are:

$$\begin{aligned} (b-v) &= S_b - S_v - 2.5 \log (d_b/d_v), \\ (u-b) &= S_u - S_b - 2.5 \log (d_u/d_b). \end{aligned} \qquad (4\text{-}12)$$

Second order extinction theory is now applied to these observed values to obtain natural (extra-atmosphere) colors and magnitudes. These quantities are denoted by zero subscripts. No second order extinction term is included in the expression for v_o, in accordance with the observed absence of any appreciable second order effect in the visual magnitudes (7). Making use of Equation (4-7) and Equation (4-8), the following are derived:

$$v_o = v - k_v X,$$

$$(b-v)_o = (b-v)(1 - k''_{bv} X) - k'_{bv} X, \quad (4-13)$$

$$(u-b)_o = (u-b)(1 - k''_{ub} X) - k'_{ub} X.$$

Using the designations

$$J_x = (1 - k''_{bv} X),$$

$$G_x = (1 - k''_{ub} X),$$

Equation (4-13) may be written as follows:

$$v_o = v - k_v X,$$

$$(b-v)_o = J_x(b-v) - k'_{bv} X, \quad (4-14)$$

$$(u-b)_o = G_x(u-b) - k'_{ub} X.$$

Assuming the validity of transformation relationships (4-9) and (4-10), the transformation from the natural system $(u, b, v)_o$ to the standard system (U, B, V) may be written as follows:

$$V = v_o + \varepsilon(B-V) + \zeta_v,$$

$$B - V = \mu(b-v)_o + \zeta_{bv}, \quad (4-15)$$

$$U - B = \Psi(u-b)_o + \zeta_{ub}.$$

Combining Equations (4-14) and Equations (4-15), the following working equations are obtained:

$$V = v - k_v X + \varepsilon(B-V) + \zeta_v,$$

$$B - V = \mu J_x(b-v) - \mu k'_{bv} X + \zeta_{bv}, \quad (4-16)$$

$$U - B = \Psi G_x(u-b) - \Psi k'_{ub} X + \zeta_{ub}.$$

These equations provide the transformation from the natural (u, b, v)$_o$ system to the standard (U, B, V) system, in terms of the constants of the natural system (ε, μ, Ψ), extinction (k_v, J_x, G_x, k'_{bv}, k'_{ub}), observed deflections, and air mass. Zero point values (ζ_v, ζ_{bv}, ζ_{ub}) can be determined, along with principal extinction coefficients, by observation of standard stars, provided the system parameters (ε, μ, Ψ) and second order extinction terms are known.

Determination of Constants

The evaluation of scale factors and extinction parameters is accomplished most precisely by separating the unknowns into groups and selecting measuring techniques which maximize the effects of the parameters under consideration while minimizing the influence of the remaining ones. For example, ε, μ, and Ψ are best determined from stars having a wide range of colors and located close together as in a cluster. The principle extinction coefficients, on the other hand, are best determined from stars of similar color differing substantially in air mass. Second order extinction parameters are best determined from differential measures on a close optical pair as it moves through a wide range of air mass.

Determination of Second Order Extinction Coefficients

Second order extinction coefficients may be determined by observing a close optical pair as it moves through a large range of air mass. If the two stars have essentially the same coordinates, then, according to Equation (4-7) and Equation (4-8) differential measures of magnitude and color will behave according to the following relationships:

$$(m_o)_1 - (m_o)_2 = m_1 - m_2 - k'' X (C_1 - C_2),$$

$$(C_o)_1 - (C_o)_2 = (C_1 - C_2) (1 - k''_c X),$$

which may be written in a more concise form using a Δ notation:

$$\Delta m_o = \Delta m - (\Delta C) k'' X, \quad (4\text{-}17)$$

$$\Delta C_o = \Delta C - (\Delta C) k''_c X. \quad (4\text{-}18)$$

For the specific case of the blue, visual, and ultraviolet color extinction parameters, Equation (4-18) may be written:

$$\Delta(b-v) = k''_{bv} X \Delta(b-v) + \Delta(b-v)_o,$$

$$\Delta(u-b) = k''_{ub} X \Delta(u-b) + \Delta(u-b)_o.$$

From this it follows that a plot of $\Delta(b-v)$ versus $X \Delta(b-v)$ yields a straight line whose slope is k''_{bv}. A similar procedure may be followed to determine k''_{ub}.

Determination of Principal Extinction Coefficients

Two methods for determining principal extinction coefficients will be discussed. The conventional method employs the observations used in the determination of second order coefficients. Assuming second order coefficients determined by the procedure previously outlined, these quantities are used in Equation (4-14) rearranged as follows:

$$(b\text{-}v)\,J_x = k'_{bv}\,X + (b\text{-}v)_o,$$

$$(u\text{-}b)\,G_x = k'_{ub}\,X + (u\text{-}b)_o, \qquad (4\text{-}19)$$

$$v = k_v\,X + v_o.$$

Therefore, a plot of $(b-v)\,J_x$ versus X yields a line whose slope is the average k'_{bv} for the time during which the observations were made. Average values for k'_{ub} and k_v are determined from similar plots. Extinction values derived by this method are most useful in a general observing program when transparency is constant.

The second method for determining principal extinction coefficients was developed by Hardie (9). This method, which involves differential measures on standard stars, assumes known values for the system constants ε, μ, and Ψ. It also assumes that the second order coefficients are known, and that only the principal coefficients are being sought.

In its simplest form, the method requires observation of two standard stars: one near zenith and the other with a substantial air mass. Expressing the measures differentially, the following expressions result from Equations (4-16):

$$k_v = \frac{\Delta v - \Delta V + \varepsilon\Delta(B-V)}{\Delta X},$$

$$k'_{bv} = \frac{\mu\Delta[J_x\,(b-v)] - \Delta(B-V)}{\mu\Delta X}, \qquad (4\text{-}20)$$

$$k'_{ub} = \frac{\Psi\Delta[G_x\,(u-b)] - \Delta(U-B)}{\Psi\Delta X}.$$

Thus, once the scale factors are well known, the expenditure of a very small quantity of observing time makes possible accurate determination of principal extinction coefficients. In an observing program, this method of evaluating extinction can be used effectively even when sky transparency is changing.

If several high stars and several low stars are observed, Equations (4-16) may be plotted to determine both extinction parameters and zero point terms. A plot of $[v + \varepsilon(B-V) - V]$ versus X gives a line whose slope is k_v. Similarly, plots of $[\mu J_x(b-v) - (B-V)]$ versus X and $[\Psi G_x(u-b) - (U-B)]$ versus X provide graphical solutions for $\mu k'_{bv}$ and $\Psi k'_{ub}$, respectively. Zero point terms may be evaluated from the intercepts.

Determination of Scale Factors

One of the most convenient methods of determining scale factors is by observation of standard stars in a cluster. The observations are treated differentially, so that extinction effects are minimized. Using approximate values for the principal extinction coefficients, such as those determined by the first extinction method discussed previously, Equations (4-19) are employed to provide v_o, $(b-v)_o$, and $(u-b)_o$ for each star observed. Using these values in Equations (4-15), graphical solutions for ε, μ, and Ψ are determined. If $(V-v_o)$ is plotted versus (B-V) for each star observed, the slope of the best fitted line is ε. The factors μ and Ψ may be determined in a similar fashion from plots of (B-V) versus $(b-v)_o$ and of (U-B) versus $(u-b)_o$.

An alternate solution for Ψ and μ is based on the following rearrangement of Equations (4-15):

$$B-V = \mu(b-v)_o + \zeta_{bv},$$

$$(B-V) - (b-v)_o = (\mu-1)\ (b-v)_o + \zeta_{bv},$$

but,

$$(b-v)_o = \frac{(B-V) - \zeta_{bv}}{\mu}\ .$$

Therefore, substitution for $(b-v)_o$ on the right side of the previous equation gives:

$$(B-V) - (b-v)_o = (1 - 1/\mu)(B-V) + \zeta_{bv}/\mu.$$

Thus, a plot of $[(B-V) - (b-v)_o]$ versus (B-V) permits a graphical solution for $(1 - 1/\mu)$ from which μ can be determined. Similarly, a plot of $[(U-B) - (u-b)_o]$ versus (U-B) leads to graphical determination of Ψ.

CHAPTER V

OBSERVING PROGRAM AND DATA REDUCTION

Observing Program Design

The observing program was designed to implement determination of the system constants (ε, μ, Ψ) and second order extinction coefficients (k''_{bv}, k''_{ub}). Consideration of star position (relative to the horizon) and telescope limitations adequately restricted choice of stars to be included in the program.

Since the observations were to take place in the late winter and early spring seasons, only those stars visible in this period could be included. This requirement led to consideration of stars having right ascension in the range four hours to nineteen hours. Similar restrictions on declination are defined by the latitude of the observatory. Due to the relatively small telescope aperture, no stars fainter than visual magnitude six were included.

Subject to the restrictions outlined above, a list of 46 standard stars was compiled. Two optical pairs (θ_1, θ_2 Tau and α_1, α_2 Lib) and nine members of the Pleiades cluster were included. Table IV contains a complete listing. Standard magnitudes and colors were obtained from Johnson and Morgan (8) and Johnson and Harris (45). Coordinate information was obtained from Becvar (53).

Observation of the optical pairs over a wide range of air mass

TABLE IV

STAR LIST

ID Number	Name	GC Number	V	B-V	U-B	Spectral Class
1	θ_1 Tau	5433	3.85	0.955	0.741	G8
2	θ_2 Tau	5436	3.41	0.179	0.132	A7
3	74 ε Tau	5430	3.52	1.011	0.878	G8
4	16 Tau	4475	5.45	-0.046	-0.33	B7
5	17 Tau	4477	3.69	-0.107	-0.41	B6
6	18 Tau	4485	5.64	-0.075	-0.36	B8
7	19 Tau	4486	4.29	-0.106	-0.46	B6
8	20 Tau	4500	3.86	-0.068	-0.40	B7
9	21 Tau	4502	5.75	-0.044	-0.23	B8
10	23 Tau	4512	4.16	-0.056	-0.43	B6
11	η Tau	4541	2.86	-0.090	-0.33	B7
12	27 Tau	4586	3.62	-0.085	-0.36	B8
13	β Ari	2309	2.65	0.13	0.10	A5
14	ο Tau	4070	3.59	0.89	0.62	G8
15	π_3 Ori	5875	3.19	0.45	-0.01	F8
16	π_4 Ori	5911	3.69	-0.17	-0.80	B2
17	η Aur	6226	3.17	-0.18	-0.67	B3
18	γ Ori	6668	1.64	-0.23	-0.87	B2
19	β Tau	6681	1.65	-0.13	-0.49	B7
20	36 υ Ori	6850	4.63	-0.26	-1.07	B0
21	44 ι Ori	6937	2.77	-0.25	-1.08	09
22	46 ε Ori	6960	1.70	-0.19	-1.04	B0
23	ζ Lep	7247	3.55	0.10	0.06	A2
24	134 Tau	7306	4.90	-0.07	-0.18	B9
25	γ Gem	8633	1.93	0.00	0.03	A0
26	54 λ Gem	9701	3.58	0.11	0.10	A3
27	ρ Gem	9987	4.16	0.32	-0.03	F0
28	77 κ Gem	10403	3.57	0.93	0.68	G8
30	11 LMi	13242	5.41	0.77	0.45	G8
31	21 LMi	13896	4.48	0.18	0.08	A7
32	α Leo	13926	1.36	-0.11	-0.36	B8
33	ρ Leo	14487	3.85	-0.14	-0.95	B1
34	90 Leo	15874	5.95	-0.16	-0.64	B3
35	β Leo	16189	2.14	0.09	0.07	A3
36	β Vir	16215	3.61	0.55	0.10	F8
37	γ Crv	16740	2.60	-0.11	-0.35	B8
38	β Com	17874	4.28	0.57	0.07	G0
39	61 Vir	18007	4.75	0.71	0.25	G5
40	α Vir	18144	0.96	-0.23	-0.94	B1
41	70 Vir	18212	4.98	0.71	0.26	G5
42	η Boo	18805	2.69	0.58	0.19	G0
43	109 Vir	19884	3.74	0.00	-0.03	A0

TABLE IV (Continued)

ID Number	Name	GC Number	V	B-V	U-B	Spectral Class
44	α_1 Lib	19970	5.16	0.41	-0.04	F4
45	α_2 Lib	19975	2.75	0.15	0.08	A3
46	α Lyr	25466	0.04	0.00	-0.01	A0
47	γ Lyr	26086	3.25	-0.05	-0.09	B9

provided data for evaluation of second order extinction parameters. Observations of the cluster stars were interspersed with those of an optical pair, on a given night, to facilitate approximate first order extinction measures. Cluster measurements were then treated differentially, as described in Chapter IV, to determine scale factors.

In addition to pair and cluster observations, measures were made on various other standard stars with the intent of providing data for more precise scale factor determinations. Stars observed for this purpose were divided into two groups. Set #1: Stars of similar color observed through substantially different air masses; Set #2: Stars having a wide range of colors observed at about the same air mass. Assuming the natural system to be fairly well matched to the standard, observational data for Set #1 and Set #2 may be used in an iterative procedure which not only effects good values for principal extinction coefficients, but also permits more precise determination of the scale factors.

Equations (4-16) are plotted, as previously described on page 75 utilizing preliminary scale factors and data from observation of Set #1. The resulting principal extinction coefficients are used in Equations (4-14) to determine v_o, $(b-v)_o$, and $(u-b)_o$ for each star in Set #2. These quantities are then utilized in plots of Equations (4-15) which yield refined values for ε, μ, and Ψ. The new values for the scale factors may then be used in Equations (4-16), and the entire process is repeated. Iteration continues until the scale factors are constant to the number of significant figures justified by experimental uncertainty.

Observing Procedure

Several preliminary preparations were necessary each evening prior to observation. It is highly desirable that the system sensitivity remain unchanged during the observations. Thus, electrical components were turned on at least one hour before any observations were made. Also, the photocathode was cooled for a minimum of one hour before making any measurements. Finally, the dome was opened sufficiently early to allow the interior to more closely approach thermal equilibrium with outside air.

The hour circle of the telescope was rectified by sighting a bright star, usually Rigel, Capella, or Betelgeuse, and setting the circle to the proper coordinate. The proper driving rate in right ascension was established by means of a variable frequency control unit incorporated in the power supply for the telescope drive mechanism. A driving rate sufficient to hold the star image in a 1 mm diaphragm aperture for at least 5 minutes was judged adequate.

About fifteen minutes before the start of the observing period, the paper drive mechanism of the chart recorder was started in coincidence with a time signal from the National Bureau of Standards radio station, WWV. The chart drive rate (0.5 inch/minute) was checked against WWV after the recorder had been running about 10 minutes. High voltage for the photomultiplier was set at 950 volts. In general, the steady state dark current was on the order of 5×10^{-11} amperes.

For each star, a total of six measurements was obtained: one star reading and one sky reading in each of the three colors. The exposure for each reading was about 15 seconds, and the star was always measured first, followed by a sky reading in the same color. Sky readings were obtained by turning the telescope in declination to move the star out of the field. The diaphragm aperture was held constant throughout the entire set of measures on a given star. In general, about 4½ minutes were required to complete the set of measurements on a single star.

The amplifier sensitivity setting was chosen to provide the largest possible star deflection. Star and sky deflections in a given color were always made with the same sensitivity setting. Star name and amplifier sensitivities were written directly on the chart recording at the time of the observation. Sky lines, average deflection lines, and times were added later to facilitate measurement of the record. Figure 17 illustratrates the form of the chart recording.

Measurement and Reduction Procedures

Preparation of the chart recording for measurement involves placing time references and drawing in the average deflection and sky lines. Time references are placed on each main scale division of the record. Since the chart drive speed was 0.5 inch per minute, each inch corresponds to a two minute time interval. Sky and star deflections, both of which may vary due to atmospheric turbulence, were averaged visually, and lines were drawn in to represent the average deflection in each case.

Measurement of the record involves determination of the net deflection for each star observation. Since the star deflection on the record includes both dark current and sky, it is necessary to subtract out these quantities to obtain the desired result. This was accomplished by graphically extrapolating the appropriate sky deflection (which included dark current) back to the time of the star reading.

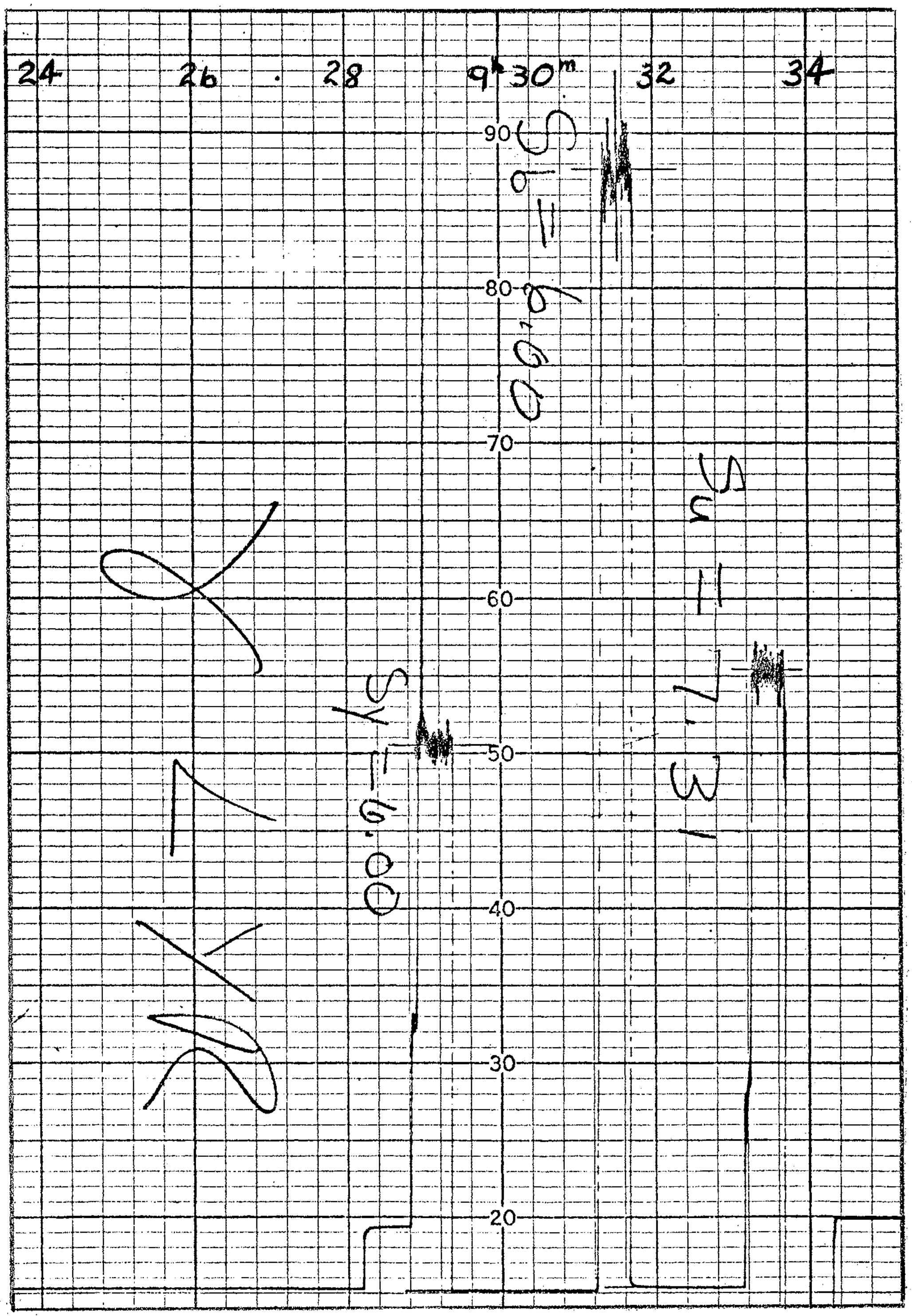

Figure 17. Chart Recording

Star deflections were then measured from the appropriate "sky line", and thus the sky and dark current were effectively subtracted out. This procedure is based on the assumption that sky and dark current did not vary appreciably in the time interval between star and sky readings. In most cases, this is plausible, since the time interval involved is about 20 seconds.

The time of the observations for a given star was taken to be the Greenwich Mean Time (GMT) corresponding to the midpoint of the blue observation. Blue was always the second of the three colors observed and thus was the middle observation.

Deflections were measured to the nearest .01 inch. Since a full scale deflection at any sensitivity setting corresponds to a 10-inch deflection on the recorder, the measured deflections were readily converted to decimal fractions of full scale for later use in Equations (4-11) and (4-12). Times were measured, using a precisely ruled scale, to the nearest five seconds. Data obtained from the chart recording for each observing session is collected in Tables V through X. The net deflection (DEFL.) and amplifier sensitivity in magnitudes (SCALE) is given for each color, along with the Greenwich Mean Time (GMT) for the set.

Reduction of the observations includes computation of air mass and determination of apparent colors and visual magnitude for each data set. Transformation from deflections to magnitude and colors is readily accomplished by use of Equations (4-11) and (4-12). Air mass determination is more tedious, involving coordinate precession, sidereal time, hour angle, and zenith distance. Once zenith distance has been determined, air mass is computed by the polynomial approximation

TABLE V

OBSERVATIONS FOR MARCH 1, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	ULTRAVIOLET DEFL.	SCALE	BLUE DEFL.	SCALE	VISUAL DEFL.	SCALE
3/ 1/69	TH1 TAU	2	50	40	0.324	9.81	0.393	7.31	0.486	7.31
3/ 1/69	TH2 TAU	3	0	20	0.479	8.50	0.292	6.00	0.729	7.31
3/ 1/69	TH1 TAU	3	56	40	0.120	9.81	0.526	8.50	0.256	7.31
3/ 1/69	TH2 TAU	4	5	20	0.229	8.50	0.493	7.31	0.444	7.31
3/ 1/69	ETA TAU	4	24	0	0.658	8.50	0.408	6.00	0.676	7.31
3/ 1/69	27 TAU	4	33	30	0.292	8.50	0.498	7.31	0.297	7.31
3/ 1/69	23 TAU	4	44	30	0.432	9.81	0.675	8.50	0.407	8.50
3/ 1/69	17 TAU	4	55	50	0.555	9.81	0.368	7.31	0.569	8.50
3/ 1/69	16 TAU	5	5	0	0.312	11.00	0.238	8.50	0.361	9.81
3/ 1/69	19 TAU	5	15	50	0.466	11.00	0.370	8.50	0.264	8.50
3/ 1/69	20 TAU	5	26	10	0.566	11.00	0.505	8.50	0.312	8.50
3/ 1/69	18 TAU	5	37	50	0.068	11.00	0.229	9.81	0.183	9.81
3/ 1/69	TH2 TAU	5	51	30	0.173	9.81	0.620	8.50	0.545	8.50
3/ 1/69	TH1 TAU	6	1	10	0.046	11.00	0.488	9.81	0.280	8.50
3/ 1/69	GAMMAGEM	6	46	40	0.465	7.31	0.346	4.81	0.569	6.00
3/ 1/69	54LAMGEM	6	56	20	0.324	8.50	0.813	7.31	0.527	7.31
3/ 1/69	RHO GEM	7	10	10	0.237	8.50	0.437	7.31	0.287	7.31
3/ 1/69	77 K GEM	7	22	0	0.305	9.81	0.418	7.31	0.482	7.31
3/ 1/69	11 LMI	7	37	0	0.025	11.00	0.288	9.81	0.504	9.81
3/ 1/69	21 LMI	7	50	20	0.474	9.81	0.309	7.31	0.697	8.50
3/ 1/69	ALPHALEO	8	5	20	0.465	6.00	0.880	4.81	0.478	4.81
3/ 1/69	RHO LEO	8	19	50	0.366	7.31	0.254	6.00	0.484	7.31
3/ 1/69	90 LEO	8	41	0	0.446	9.81	0.418	8.50	0.621	9.81
3/ 1/69	BETA LEO	8	57	50	0.575	7.31	0.395	4.81	0.878	6.00

TABLE VI

OBSERVATIONS FOR MARCH 5, 1969

DATE	STAR	TIME (GMT)			ULTRAVIOLET		BLUE		VISUAL	
		HR	MIN	SEC	DEFL.	SCALE	DEFL.	SCALE	DEFL.	SCALE
3/ 5/69	TH1 TAU	2	8	10	0.441	9.81	0.571	7.31	0.718	7.31
3/ 5/69	TH2 TAU	2	15	50	0.687	8.50	0.479	6.00	0.336	6.00
3/ 5/69	74EP TAU	2	23	20	0.427	9.81	0.598	7.31	0.274	6.00
3/ 5/69	BETA ARI	2	32	20	0.478	8.50	0.474	6.00	0.472	6.00
3/ 5/69	TH1 TAU	2	43	50	0.366	9.81	0.405	7.31	0.672	7.31
3/ 5/69	TH2 TAU	2	51	10	0.605	8.50	0.480	6.00	0.308	6.00
3/ 5/69	ETA TAU	3	1	10	0.603	7.31	0.808	6.00	0.468	6.00
3/ 5/69	27 TAU	3	8	50	0.291	7.31	0.422	6.00	0.800	7.31
3/ 5/69	23 TAU	3	18	40	0.496	8.50	0.799	7.31	0.475	7.31
3/ 5/69	TH1 TAU	3	28	20	0.304	9.81	0.416	7.31	0.619	7.31
3/ 5/69	TH2 TAU	3	36	10	0.468	8.50	0.384	6.00	0.278	6.00
3/ 5/69	17 TAU	3	45	20	0.608	8.50	0.316	6.00	0.709	7.31
3/ 5/69	16 TAU	3	52	20	0.251	9.81	0.632	8.50	0.389	8.50
3/ 5/69	19 TAU	4	0	10	0.330	8.50	0.187	6.00	0.343	7.31
3/ 5/69	20 TAU	4	5	20	0.433	8.50	0.243	6.00	0.477	7.31
3/ 5/69	TH1 TAU	4	12	50	0.218	9.81	0.349	7.31	0.509	7.31
3/ 5/69	TH2 TAU	4	20	30	0.311	8.50	0.304	6.00	0.216	6.00
3/ 5/69	18 TAU	4	32	0	0.152	9.81	0.346	8.50	0.252	8.50
3/ 5/69	21 TAU	4	41	0	0.093	9.81	0.262	8.50	0.191	8.50
3/ 5/69	TH1 TAU	4	51	10	0.112	9.81	0.248	7.31	0.407	7.31
3/ 5/69	TH2 TAU	4	57	20	0.512	9.81	0.191	6.00	0.173	6.00
3/ 5/69	TH2 TAU	5	35	50	0.146	9.81	0.303	7.31	0.367	7.31
3/ 5/69	TH1 TAU	5	41	30	0.060	11.00	0.263	8.50	0.550	8.50
3/ 5/69	PI4 ORI	5	54	20	0.050	9.81	0.230	8.50	0.160	8.50
3/ 5/69	PI3 ORI	6	3	10	0.020	11.00	0.084	8.50	0.141	8.50
3/ 5/69	ALPHALEO	6	16	0	0.329	4.81	0.421	3.50	0.695	4.81

TABLE VII

OBSERVATIONS FOR MARCH 19, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	ULTRAVIOLET DEFL.	SCALE	BLUE DEFL.	SCALE	VISUAL DEFL.	SCALE
3/19/69	TH1 TAU	2	17	5	0.487	9.81	0.389	7.31	0.623	7.31
3/19/69	TH2 TAU	2	22	55	0.644	8.50	0.466	6.00	0.393	6.00
3/19/69	BETA ARI	2	30	35	0.250	8.50	0.380	6.00	0.313	6.00
3/19/69	74EP TAU	2	40	45	0.488	9.81	0.640	7.31	0.844	7.31
3/19/69	TH1 TAU	2	51	15	0.902	11.00	0.350	7.31	0.575	7.31
3/19/69	TH2 TAU	3	2	40	0.486	8.50	0.385	6.00	0.851	7.31
3/19/69	ETA TAU	3	11	25	0.569	7.31	0.776	6.00	0.410	6.00
3/19/69	27 TAU	3	19	50	0.783	8.50	0.395	6.00	0.691	7.31
3/19/69	TH1 TAU	3	28	30	0.323	9.81	0.437	7.31	0.535	7.31
3/19/69	TH2 TAU	3	34	45	0.495	8.50	0.388	6.00	0.876	7.31
3/19/69	23 TAU	3	43	45	0.396	8.50	0.679	7.31	0.381	7.31
3/19/69	17 TAU	3	50	15	0.543	8.50	0.303	6.00	0.525	7.31
3/19/69	19 TAU	3	56	30	0.318	8.50	0.569	7.31	0.318	7.31
3/19/69	20 TAU	4	5	20	0.647	9.81	0.632	7.31	0.443	7.31
3/19/69	TH1 TAU	4	16	5	0.488	11.00	0.299	7.31	0.440	7.31
3/19/69	TH2 TAU	4	21	15	0.442	9.81	0.350	7.31	0.507	7.31
3/19/69	PI3 ORI	4	31	20	0.198	8.50	0.609	7.31	0.596	7.31
3/19/69	PI4 ORI	4	37	30	0.347	8.50	0.624	7.31	0.415	7.31
3/19/69	ETA AUR	4	47	25	0.570	7.31	0.554	6.00	0.264	6.00
3/19/69	RHO LEO	5	5	20	0.453	7.31	0.565	6.00	0.273	6.00
3/19/69	BETA LEO	5	24	10	0.300	6.00	0.599	4.81	0.738	6.00
3/19/69	GAMMACRV	5	40	0	0.809	7.31	0.390	4.81	0.551	6.00
3/19/69	ALPH VIR	5	50	40	0.696	4.81	0.413	3.50	0.805	4.81
3/19/69	70 VIR	6	10	25	0.329	9.81	0.681	8.50	0.610	8.50
3/19/69	ALPH2LIB	6	24	15	0.503	8.50	0.512	6.00	0.355	6.00
3/19/69	ALPH1LIB	6	30	10	0.664	11.00	0.517	8.50	0.449	8.50

TABLE VIII

OBSERVATIONS FOR MARCH 28, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	ULTRAVIOLET DEFL.	SCALE	BLUE DEFL.	SCALE	VISUAL DEFL.	SCALE
3/28/69	TH1 TAU	2	43	30	0.320	9.81	0.356	7.31	0.460	7.31
3/28/69	TH2 TAU	2	48	10	0.430	8.50	0.312	6.00	0.732	7.31
3/28/69	74EP TAU	2	58	35	0.286	9.81	0.461	7.31	0.600	9.81
3/28/69	TH1 TAU	3	5	30	0.699	11.00	0.334	7.31	0.438	7.31
3/28/69	TH2 TAU	3	10	15	0.352	8.50	0.269	6.00	0.636	7.31
3/28/69	ETA TAU	3	20	25	0.739	8.50	0.455	6.00	0.275	6.00
3/28/69	TH1 TAU	3	27	30	0.560	11.00	0.854	8.50	0.414	7.31
3/28/69	TH2 TAU	3	31	20	0.278	8.50	0.804	7.31	0.602	7.31
3/28/69	27 TAU	3	39	45	0.279	8.50	0.646	7.31	0.417	7.31
3/28/69	TH1 TAU	3	45	55	0.407	11.00	0.243	7.31	0.367	7.31
3/28/69	TH2 TAU	3	51	40	0.570	9.81	0.675	7.31	0.511	7.31
3/28/69	23 TAU	4	2	15	0.210	9.81	0.644	8.50	0.482	8.50
3/28/69	TH1 TAU	4	9	25	0.239	11.00	0.529	8.50	0.833	8.50
3/28/69	TH2 TAU	4	13	45	0.285	9.81	0.458	7.31	0.427	7.31
3/28/69	BETA TAU	4	39	10	0.402	6.00	0.595	4.81	0.331	4.81
3/28/69	GAMMAGEM	4	50	0	0.715	7.31	0.505	4.81	0.749	6.00
3/28/69	54LAMGEM	4	59	30	0.522	8.50	0.332	6.00	0.704	7.31
3/28/69	RHO GEM	5	6	40	0.327	8.50	0.610	7.31	0.419	7.31
3/28/69	77 K GEM	5	15	25	0.500	9.81	0.564	7.31	0.645	7.31
3/28/69	ALPH2LIB	5	39	35	0.439	8.50	0.404	6.00	0.303	6.00

TABLE IX

OBSERVATIONS FOR APRIL 6, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	ULTRAVIOLET DEFL.	SCALE	BLUE DEFL.	SCALE	VISUAL DEFL.	SCALE
4/ 6/69	ALPH2LIB	9	19	10	0.705	8.50	0.479	6.00	0.313	6.00
4/ 6/69	ALPH1LIB	9	26	5	0.632	11.00	0.400	8.50	0.332	8.50
4/ 6/69	BETA COM	9	37	50	0.500	9.81	0.320	7.31	0.281	7.31
4/ 6/69	ALPH2LIB	9	45	25	0.579	8.50	0.428	6.00	0.281	6.00
4/ 6/69	ALPH1LIB	9	51	30	0.574	11.00	0.364	8.50	0.297	8.50
4/ 6/69	ALPH VIR	10	4	35	0.630	6.00	0.749	4.81	0.413	4.81
4/ 6/69	ALPH1LIB	10	13	40	0.489	11.00	0.334	8.50	0.260	8.50
4/ 6/69	ALPH2LIB	10	19	30	0.475	8.50	0.371	6.00	0.871	7.31
4/ 6/69	ETA BOO	10	30	20	0.530	8.50	0.320	6.00	0.300	6.00
4/ 6/69	ALPH2LIB	10	39	5	0.395	8.50	0.310	6.00	0.218	6.00
4/ 6/69	ALPH1LIB	10	43	55	0.389	11.00	0.265	8.50	0.226	8.50
4/ 6/69	109 VIR	11	2	10	0.289	8.50	0.601	7.31	0.362	7.31
4/ 6/69	ALPH1LIB	11	9	40	0.278	11.00	0.197	8.50	0.174	8.50
4/ 6/69	ALPH2LIB	11	14	25	0.715	9.81	0.741	7.31	0.598	7.31
4/ 6/69	ALPH LYR	11	25	25	0.484	4.81	0.727	3.50	0.389	3.50
4/ 6/69	GAMMALYR	11	34	40	0.557	8.50	0.390	6.00	0.676	7.31

TABLE X

OBSERVATIONS FOR MAY 11, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	ULTRAVIOLET DEFL.	SCALE	BLUE DEFL.	SCALE	VISUAL DEFL.	SCALE
5/11/69	ALPHALEO	5	3	25	0.760	6.00	0.348	3.50	0.589	4.81
5/11/69	RHO LEO	5	11	35	0.508	7.31	0.381	6.00	0.625	7.31
5/11/69	BETA LEO	5	31	0	0.935	7.31	0.604	4.81	0.335	4.81
5/11/69	BETA VIR	5	43	5	0.417	8.50	0.860	7.31	0.744	7.31
5/11/69	GAMMACRV	5	56	30	0.556	7.31	0.312	4.81	0.472	6.00
5/11/69	BETA COM	6	44	10	0.920	9.81	0.541	7.31	0.459	7.31
5/11/69	61 VIR	6	55	5	0.663	11.00	0.584	8.50	0.621	8.50
5/11/69	ALPH1LIB	7	8	10	0.331	9.81	0.648	8.50	0.516	8.50
5/11/69	ALPH2LIB	7	16	15	0.364	7.31	0.255	4.81	0.440	6.00
5/11/69	ALPH VIR	7	25	5	0.533	4.81	0.474	3.50	0.229	3.50
5/11/69	ALPH1LIB	7	35	30	0.312	9.81	0.640	8.50	0.470	8.50
5/11/69	ALPH2LIB	7	41	50	0.311	7.31	0.245	4.81	0.452	6.00
5/11/69	70 VIR	8	1	40	0.853	11.00	0.623	8.50	0.613	8.50
5/11/69	ALPH2LIB	8	12	5	0.855	8.50	0.633	6.00	0.418	6.00
5/11/69	ALPH1LIB	8	18	20	0.827	11.00	0.568	8.50	0.450	8.50
5/11/69	ETA BOO	8	26	50	0.884	8.50	0.573	6.00	0.512	6.00
5/11/69	ALPH2LIB	8	37	30	0.729	8.50	0.531	6.00	0.380	6.00
5/11/69	ALPH1LIB	8	43	20	0.680	11.00	0.511	8.50	0.430	8.50
5/11/69	109 VIR	8	52	40	0.589	8.50	0.350	6.00	0.649	7.31
5/11/69	ALPH1LIB	9	3	25	0.537	11.00	0.459	8.50	0.414	8.50
5/11/69	ALPH2LIB	9	10	35	0.544	8.50	0.465	6.00	0.333	6.00
5/11/69	GAMMALYR	9	31	30	0.497	7.31	0.725	6.00	0.356	6.00
5/11/69	ALPH LYR	9	47	50	0.280	3.50	0.501	2.31	0.242	2.31
5/11/69	ALPH1LIB	9	59	30	0.176	11.00	0.670	9.81	0.765	9.81
5/11/69	ALPH2LIB	10	4	55	0.486	9.81	0.755	7.31	0.646	7.31

given on page 64. In view of the large number of calculations involved, a computer program was written to handle reduction of the observations. The source program listing and input format specifications may be found in Appendix A. Reductions are compiled in Tables XI through XVI. Since the computer printout uses only capital letters, some explanation is required to clarify the notation. The column headings "MAGNITUDE" and "COLOR" refer to visual magnitude and colors, uncorrected for extinction, observed with the Enid System. The final three columns of each table "STANDARD VALUES", contain magnitudes and colors published by Johnson and Morgan (8) or Johnson and Harris (45).

Analysis

General Method and Error Determination

The methods for determining scale factors and extinction parameters were discussed in the final section of Chapter IV. It will be recalled that all of the methods, in the final step, involve fitting a straight line to a set of data points. The slope of the line is then measured to determine the desired quantity.

The problem of finding the "best fitted" straight line for a set of data points is readily handled by the well known Method of Least Squares, and that is the method employed in the present case. Scarborough (54) discusses this method in detail on pages 533-541.

Computer techniques were used to implement the method. A very general program, designed to provide a least squares fit of any specified polynomial to a set of data points, was utilized to obtain a linear fit. The slope of the line comes out in the solution as the coef-

TABLE XI

REDUCED DATA FOR MARCH 1, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	RELATIVE AIR MASS	MAGNITUDE V	COLOR B-V	U-B	STANDARD VALUES V	B-V	U-B	
3/ 1/69	TH1 TAU	2	50	40	1.274	8.093	0.231	2.710	3.850	0.955	0.741	
3/ 1/69	TH2 TAU	3	0	20	1.308	7.653	-0.317	1.963	3.410	0.179	0.132	
3/ 1/69	TH1 TAU	3	56	40	1.592	8.789	0.408	2.915	3.850	0.955	0.741	
3/ 1/69	TH2 TAU	4	5	20	1.655	8.192	-0.114	2.023	3.410	0.179	0.132	
3/ 1/69	ETA TAU	4	24	0	2.035	7.735	-0.762	1.981	2.860	-0.090	-0.330	*
3/ 1/69	27 TAU	4	33	30	2.140	8.628	-0.561	1.770	3.620	-0.085	-0.360	*
3/ 1/69	23 TAU	4	44	30	2.359	9.476	-0.549	1.795	4.160	-0.056	-0.430	*
3/ 1/69	17 TAU	4	55	50	2.594	9.112	-0.717	2.054	3.690	-0.107	-0.410	*
3/ 1/69	16 TAU	5	5	0	2.794	10.916	-0.858	2.206	5.450	-0.046	-0.330	*
3/ 1/69	19 TAU	5	15	50	3.063	9.946	-0.366	2.250	4.290	-0.106	-0.460	*
3/ 1/69	20 TAU	5	26	10	3.391	9.765	-0.523	2.376	3.860	-0.068	-0.400	*
3/ 1/69	18 TAU	5	37	50	3.844	11.654	-0.243	2.508	5.640	-0.075	-0.360	*
3/ 1/69	TH2 TAU	5	51	30	3.645	9.159	-0.140	2.696	3.410	0.179	0.132	*
3/ 1/69	TH1 TAU	6	1	10	4.118	9.882	0.707	3.754	3.850	0.955	0.741	*
3/ 1/69	GAMMAGEM	6	46	40	1.944	6.612	-0.650	2.179	1.930	0.0	0.030	
3/ 1/69	54LAMGEM	6	56	20	1.654	8.005	-0.471	2.189	3.580	0.110	0.100	
3/ 1/69	RHO GEM	7	10	10	1.447	8.665	-0.456	1.854	4.160	0.320	-0.030	
3/ 1/69	77 K GEM	7	22	0	1.515	8.102	0.155	2.842	3.570	0.930	0.680	
3/ 1/69	11 LMI	7	37	0	1.107	10.554	0.608	3.844	5.410	0.770	0.450	
3/ 1/69	21 LMI	7	50	20	1.077	8.892	-0.307	2.035	4.480	0.180	0.080	
3/ 1/69	ALPHALEO	8	5	20	1.245	5.611	-0.663	1.883	1.360	-0.110	-0.360	
3/ 1/69	RHO LEO	8	19	50	1.251	8.098	-0.610	0.913	3.850	-0.140	-0.950	
3/ 1/69	90 LEO	8	41	0	1.103	10.327	-0.880	1.240	5.950	-0.160	-0.640	
3/ 1/69	BETA LEO	8	57	50	1.124	6.141	-0.323	2.092	2.140	0.090	0.070	

* STAR WITHIN 30 DEGREES OF HORIZON

TABLE XII

REDUCED DATA FOR MARCH 5, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	RELATIVE AIR MASS	MAGNITUDE V	COLOR B-V	U-B	STANDARD VALUES V	B-V	U-B	
3/ 5/69	TH1 TAU	2	8	10	1.198	7.670	0.249	2.780	3.850	0.955	0.741	
3/ 5/69	TH2 TAU	2	15	50	1.218	7.184	-0.385	2.108	3.410	0.179	0.132	
3/ 5/69	74EP TAU	2	23	20	1.208	7.406	0.463	2.866	3.520	1.011	0.878	
3/ 5/69	BETA ARI	2	32	20	2.415	6.815	-0.005	2.491	2.650	0.130	0.100	*
3/ 5/69	TH1 TAU	2	43	50	1.305	7.742	0.550	2.610	3.850	0.955	0.741	
3/ 5/69	TH2 TAU	2	51	10	1.333	7.279	-0.482	2.249	3.410	0.179	0.132	
3/ 5/69	ETA TAU	3	1	10	1.470	6.824	-0.593	1.628	2.860	-0.090	-0.330	
3/ 5/69	27 TAU	3	8	50	1.505	7.552	-0.616	1.714	3.620	-0.085	-0.360	
3/ 5/69	23 TAU	3	18	40	1.587	8.118	-0.565	1.708	4.160	-0.056	-0.430	
3/ 5/69	TH1 TAU	3	28	20	1.511	7.831	0.431	2.841	3.850	0.955	0.741	
3/ 5/69	TH2 TAU	3	36	10	1.561	7.390	-0.351	2.285	3.410	0.179	0.132	
3/ 5/69	17 TAU	3	45	20	1.812	7.683	-0.433	1.789	3.690	-0.107	-0.410	
3/ 5/69	16 TAU	3	52	20	1.878	9.525	-0.527	2.313	5.450	-0.046	-0.330	
3/ 5/69	19 TAU	4	0	10	1.955	8.472	-0.651	1.883	4.290	-0.106	-0.460	
3/ 5/69	20 TAU	4	5	20	2.011	8.114	-0.578	1.873	3.860	-0.068	-0.400	*
3/ 5/69	TH1 TAU	4	12	50	1.859	8.043	0.410	3.011	3.850	0.955	0.741	
3/ 5/69	TH2 TAU	4	20	30	1.943	7.664	-0.371	2.475	3.410	0.179	0.132	
3/ 5/69	18 TAU	4	32	0	2.395	9.996	-0.344	2.203	5.640	-0.075	-0.360	*
3/ 5/69	21 TAU	4	41	0	2.567	10.297	-0.343	2.435	5.750	-0.044	-0.230	*
3/ 5/69	TH1 TAU	4	51	10	2.380	8.286	0.538	3.363	3.850	0.955	0.741	*
3/ 5/69	TH2 TAU	4	57	20	2.500	7.905	-0.107	2.739	3.410	0.179	0.132	*
3/ 5/69	TH2 TAU	5	35	50	3.648	8.398	0.208	3.293	3.410	0.179	0.132	*
3/ 5/69	TH1 TAU	5	41	30	3.907	9.149	0.801	4.105	3.850	0.955	0.741	*
3/ 5/69	P14 ORI	5	54	20	5.275	10.490	-0.394	2.967	3.690	-0.170	-0.800	*
3/ 5/69	P13 ORI	6	3	10	5.937	10.627	0.562	4.058	3.190	0.450	-0.010	*
3/ 5/69	ALPHALEO	6	16	0	1.104	5.205	-0.766	1.578	1.360	-0.110	-0.360	

* STAR WITHIN 30 DEGREES OF HORIZON

TABLE XIII

REDUCED DATA FOR MARCH 19, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	RELATIVE AIR MASS	MAGNITUDE V	COLOR B-V	U-B	STANDARD VALUES V	B-V	U-B	
3/19/69	TH1 TAU	2	17	5	1.424	7.824	0.511	2.256	3.850	0.955	0.741	
3/19/69	TH2 TAU	2	22	55	1.455	7.014	-0.185	2.149	3.410	0.179	0.132	
3/19/69	BETA ARI	2	30	35	4.120	7.261	-0.211	2.955	2.650	0.130	0.100	*
3/19/69	74EP TAU	2	40	45	1.503	7.494	0.300	2.794	3.520	1.011	0.878	
3/19/69	TH1 TAU	2	51	15	1.629	7.911	0.539	2.662	3.850	0.955	0.741	
3/19/69	TH2 TAU	3	2	40	1.720	7.485	-0.449	2.247	3.410	0.179	0.132	
3/19/69	ETA TAU	3	11	25	2.012	6.968	-0.693	1.647	2.860	-0.090	-0.330	*
3/19/69	27 TAU	3	19	50	2.100	7.711	-0.703	1.757	3.620	-0.085	-0.360	*
3/19/69	TH1 TAU	3	28	30	1.976	7.989	0.220	2.828	3.850	0.955	0.741	
3/19/69	TH2 TAU	3	34	45	2.056	7.454	-0.426	2.236	3.410	0.179	0.132	*
3/19/69	23 TAU	3	43	45	2.546	8.358	-0.627	1.775	4.160	-0.056	-0.430	*
3/19/69	17 TAU	3	50	15	2.709	8.010	-0.713	1.867	3.690	-0.107	-0.410	*
3/19/69	19 TAU	3	56	30	2.829	8.554	-0.632	1.822	4.290	-0.106	-0.460	*
3/19/69	20 TAU	4	5	20	3.060	8.194	-0.386	2.475	3.860	-0.068	-0.400	*
3/19/69	TH1 TAU	4	16	5	2.809	8.201	0.419	3.158	3.850	0.955	0.741	*
3/19/69	TH2 TAU	4	21	15	2.954	8.047	0.402	2.247	3.410	0.179	0.132	*
3/19/69	PI3 ORI	4	31	20	3.425	7.872	-0.023	2.410	3.190	0.450	-0.010	*
3/19/69	PI4 ORI	4	37	30	3.804	8.265	-0.443	1.827	3.690	-0.170	-0.800	*
3/19/69	ETA AUR	4	47	25	1.795	7.446	-0.805	1.279	3.170	-0.180	-0.670	
3/19/69	RHO LEO	5	5	20	1.123	7.410	-0.790	1.550	3.850	-0.140	-0.950	
3/19/69	BETA LEO	5	24	10	1.118	6.330	-0.963	1.941	2.140	0.090	0.070	
3/19/69	GAMMACRV	5	40	0	1.833	6.647	-0.815	1.708	2.600	-0.110	-0.350	
3/19/69	ALPH VIR	5	50	40	1.862	5.046	-0.585	0.743	0.960	-0.230	-0.940	
3/19/69	70 VIR	6	10	25	1.226	9.037	-0.120	2.100	4.980	0.710	0.260	
3/19/69	ALPH2LIB	6	24	15	2.778	7.124	-0.398	2.519	2.750	0.150	0.080	*
3/19/69	ALPH1LIB	6	30	10	2.663	9.369	-0.153	2.228	5.160	0.410	-0.040	*

* STAR WITHIN 30 DEGREES OF HORIZON

TABLE XIV

REDUCED DATA FOR MARCH 28, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	RELATIVE AIR MASS	MAGNITUDE V	COLOR B-V	U-B	STANDARD VALUES V	B-V	U-B	
3/28/69	TH1 TAU	2	43	30	1.870	8.153	0.278	2.616	3.850	0.955	0.741	
3/28/69	TH2 TAU	2	48	10	1.922	7.649	-0.384	2.152	3.410	0.179	0.132	
3/28/69	74EP TAU	2	58	35	1.941	10.365	-2.214	3.018	3.520	1.011	0.878	
3/28/69	TH1 TAU	3	5	30	2.136	8.206	0.294	2.888	3.850	0.955	0.741	*
3/28/69	TH2 TAU	3	10	15	2.209	7.801	-0.376	2.208	3.410	0.179	0.132	*
3/28/69	ETA TAU	3	20	25	2.779	7.402	-0.547	1.973	2.860	-0.090	-0.330	*
3/28/69	TH1 TAU	3	27	30	2.509	8.267	0.404	2.958	3.850	0.955	0.741	*
3/28/69	TH2 TAU	3	31	20	2.592	7.861	-0.314	2.343	3.410	0.179	0.132	*
3/28/69	27 TAU	3	39	45	3.295	8.260	-0.475	2.102	3.620	-0.085	-0.360	*
3/28/69	TH1 TAU	3	45	55	2.951	8.398	0.448	3.130	3.850	0.955	0.741	*
3/28/69	TH2 TAU	3	51	40	3.130	8.039	-0.302	2.684	3.410	0.179	0.132	*
3/28/69	23 TAU	4	2	15	4.501	9.292	-0.315	2.527	4.160	-0.056	-0.430	*
3/28/69	TH1 TAU	4	9	25	3.825	8.698	0.493	3.363	3.850	0.955	0.741	*
3/28/69	TH2 TAU	4	13	45	4.057	8.234	-0.076	3.015	3.410	0.179	0.132	*
3/28/69	BETA TAU	4	39	10	2.189	6.010	-0.637	1.616	1.650	-0.130	-0.490	*
3/28/69	GAMMAGEM	4	50	0	1.832	6.314	-0.762	2.122	1.930	0.0	0.030	
3/28/69	54LAMGEM	4	59	30	1.578	7.691	-0.494	2.009	3.580	0.110	0.100	
3/28/69	RHO GEM	5	6	40	1.364	8.254	-0.408	1.867	4.160	0.320	-0.030	
3/28/69	77 K GEM	5	15	25	1.404	7.786	0.146	2.631	3.570	0.930	0.680	
3/28/69	ALPH2LIB	5	39	35	2.972	7.296	-0.312	2.410	2.750	0.150	0.080	*

* STAR WITHIN 30 DEGREES OF HORIZON

TABLE XV

REDUCED DATA FOR APRIL 6, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	RELATIVE AIR MASS	MAGNITUDE V	COLOR B-V	U-B	STANDARD VALUES V	B-V	U-B	
4/ 6/69	ALPH2LIB	9	19	10	1.695	7.261	-0.462	2.080	2.750	0.150	0.080	
4/ 6/69	ALPH1LIB	9	26	5	1.711	9.697	-0.202	2.003	5.160	0.410	-0.040	
4/ 6/69	BETA COM	9	37	50	1.254	8.688	-0.141	2.015	4.280	0.570	0.070	
4/ 6/69	ALPH2LIB	9	45	25	1.773	7.378	-0.457	2.172	2.750	0.150	0.080	
4/ 6/69	ALPH1LIB	9	51	30	1.796	9.818	-0.221	2.005	5.160	0.410	-C.040	
4/ 6/69	ALPH VIR	10	4	35	2.319	5.770	-0.646	1.378	0.960	-0.230	-C.940	*
4/ 6/69	ALPH1LIB	10	13	40	1.903	9.963	-0.272	2.086	5.160	0.410	-0.040	
4/ 6/69	ALPH2LIB	10	19	30	1.938	7.460	-0.383	2.232	2.750	0.150	0.080	
4/ 6/69	ETA BOO	10	30	20	1.384	7.307	-0.070	1.952	2.690	0.580	0.190	
4/ 6/69	ALPH2LIB	10	39	5	2.076	7.654	-0.382	2.237	2.750	0.150	0.080	*
4/ 6/69	ALPH1LIB	10	43	55	2.116	10.115	-0.173	2.083	5.160	0.410	-0.040	*
4/ 6/69	109 VIR	11	2	10	1.585	8.413	-0.550	1.985	3.740	0.0	-0.030	
4/ 6/69	ALPH1LIB	11	9	40	2.388	10.399	-0.135	2.126	5.160	0.410	-0.040	*
4/ 6/69	ALPH2LIB	11	14	25	2.451	7.868	-0.233	2.539	2.750	0.150	0.080	*
4/ 6/69	ALPH LYR	11	25	25	1.013	4.525	-0.679	1.752	0.040	0.0	-0.010	
4/ 6/69	GAMMALYR	11	34	40	1.024	7.735	-0.713	2.113	3.250	-0.050	-0.090	

* STAR WITHIN 30 DEGREES OF HORIZON

TABLE XVI

REDUCED DATA FOR MAY 11, 1969

DATE	STAR	TIME (GMT) HR	MIN	SEC	RELATIVE AIR MASS	MAGNITUDE V	COLOR B-V	U-B	STANDARD VALUES V	B-V	U-B	
5/11/69	ALPHALEO	5	3	25	1.727	5.385	-0.739	1.652	1.360	-0.110	-0.360	
5/11/69	RHO LEO	5	11	35	1.664	7.820	-0.773	0.998	3.850	-0.140	-0.950	
5/11/69	BETA LEO	5	31	0	1.287	5.997	-0.640	2.026	2.140	0.090	0.070	
5/11/69	BETA VIR	5	43	5	1.551	7.631	-0.157	1.976	3.610	0.550	0.100	
5/11/69	GAMMACRV	5	56	30	2.252	6.815	-0.741	1.873	2.600	-0.110	-0.350	*
5/11/69	BETA COM	6	44	10	1.153	8.155	-0.178	1.924	4.280	0.570	0.070	
5/11/69	61 VIR	6	55	5	2.266	9.017	0.067	2.362	4.750	0.710	0.250	*
5/11/69	ALPH1LIB	7	8	10	1.710	9.218	-0.247	2.039	5.160	0.410	-0.040	
5/11/69	ALPH2LIB	7	16	15	1.734	6.891	-0.598	2.114	2.750	0.150	0.080	
5/11/69	ALPH VIR	7	25	5	2.068	5.100	-0.790	1.183	0.960	-0.230	-0.940	*
5/11/69	ALPH1LIB	7	35	30	1.802	9.320	-0.335	2.090	5.160	0.410	-0.040	
5/11/69	ALPH2LIB	7	41	50	1.831	6.862	-0.525	2.241	2.750	0.150	0.080	
5/11/69	70 VIR	8	1	40	1.535	9.031	-0.018	2.159	4.980	0.710	0.260	
5/11/69	ALPH2LIB	8	12	5	2.005	6.947	-0.451	2.174	2.750	0.150	0.080	*
5/11/69	ALPH1LIB	8	18	20	2.051	9.367	-0.253	2.092	5.160	0.410	-0.040	*
5/11/69	ETA BOO	8	26	50	1.453	6.727	-0.122	2.029	2.690	0.580	0.190	
5/11/69	ALPH2LIB	8	37	30	2.222	7.051	-0.363	2.156	2.750	0.150	0.080	*
5/11/69	ALPH1LIB	8	43	20	2.284	9.416	-0.187	2.190	5.160	0.410	-0.040	*
5/11/69	109 VIR	8	52	40	1.634	7.779	-0.640	1.935	3.740	0.0	-0.030	
5/11/69	ALPH1LIB	9	3	25	2.546	9.457	-0.112	2.330	5.160	0.410	-0.040	*
5/11/69	ALPH2LIB	9	10	35	2.663	7.194	-0.363	2.330	2.750	0.150	0.080	*
5/11/69	GAMMALYR	9	31	30	1.014	7.121	-0.772	1.720	3.250	-0.050	-0.090	
5/11/69	ALPH LYR	9	47	50	1.001	3.850	-0.790	1.822	0.040	0.0	-0.010	
5/11/69	ALPH1LIB	9	59	30	4.065	10.101	0.144	2.641	5.160	0.410	-0.040	*
5/11/69	ALPH2LIB	10	4	55	4.338	7.784	-0.169	2.978	2.750	0.150	0.080	*

* STAR WITHIN 30 DEGREES OF HORIZON

ficient of the first power term. The source program listing and input format specifications may be found in Appendix A.

It is important that any experimentally determined quantity be accompanied by an estimate of precision. In many cases, including the present one, it is prohibitively difficult to trace the propagation of known errors in the data through the calculations to determine absolute errors, or even upper bounds for errors in the computed quantities. An alternate approach was used to estimate probable relative errors in the various computed quantities.

In general, the probable error of a single determination in a series of measurements is a quantity such that one half the errors of the series are greater than it and the other half less than it. Relative error refers to the quotient obtained when the absolute error in a measured quantity is divided by the magnitude of the measured quantity. Probable relative error, then, is the relative error bound for which the probability is ½.

Scarborough (54) discusses, in section 159, the use of residuals in determining the probable error of a single trial in a series of measurements. Such a determination was included in the least squares analysis, the residuals in the ordinates being computed at the given abcissa values with respect to the best fitted line. This approach assumes the x values to be exact, and the "scatter" of the y values around the best fitted line is attributed to errors in the y values alone. Obviously, this is not entirely true in the present application; thus, the precision measures resulting from this error analysis are most appropriately used in comparing the precision of the various computed quantities with one another, rather than in any absolute sense.

Thus, each least squares solution was accompanied by a value for the probable error in any single y coordinate included in the given set of data points. This value was used to determine an average probable relative error in y for each data set. This average quantity was found by dividing the probable error for the set by each of the given y values and taking the arithmetic mean of the resulting numbers. Thus, for each slope determined by the least squares method, an average probable relative error in the y coordinates of the associated data set was available.

Next, the process graph procedure described by McCracken and Dorn (55) in Section 2.7 was employed to evaluate the propagation of a known relative error in y through a calculation of slope for a straight line. Again, x values were assumed to be precisely known. The result of this analysis is not surprising, in view of the assumptions made. The relative error in the slope of the line is the relative error in y plus roundoff errors. In the present case, roundoff errors are negligible. Thus, for each quantity determined from the slope of a best fitted straight line, a probable relative error was also determined. Following the methods discussed by Scarborough (54) in section 160, relative weights and probable relative errors of weighted means were computed.

Second Order Extinction Coefficients

Second order extinction parameters were determined by differential treatment of the optical pair data. For each observation of a given pair, an average air mass was determined and used in the calculations. Preliminary plots of Equation (4-18) for each night revealed certain points which obviously fell far from the general trend of the data.

The corresponding coordinates were subsequently omitted from the analysis. For this reason, the data collected on March 19 was entirely deleted. The extinction values determined from the θ_1, θ_2 Tau observations were the only ones included in the weighted average. Due to the close proximity of θ_1, θ_2 Tau to the Pleiades, the second order values based on this pair were judged more reliable for use with Pleiades data than those based on the α_1, α_2 Lib observations. The calculations are summarized in Table XVII.

Approximate First Order Extinction Coefficients

Approximate values for the principal extinction terms are needed for use with the Pleiades data in the determination of scale factors. These approximate extinction values were found for each of the March observing sessions by conventional use of the θ_1, θ_2 Tau data in Equations (4-19). The separate determinations were averaged with equal weight, except in cases where the probable error differed by an order of magnitude. The results are summarized in Table XVIII.

Scale Factors

Scale factors were determined by the method discussed on page 75 of Chapter IV. Pleiades data were combined with the appropriate extinction parameters for each of the four March dates. Pertinent observational data, natural magnitudes and colors, and standard magnitudes and colors are compiled in Tables XIX through XXII.

Values for ε, μ, Ψ were determined for each date, and these individual results were combined to give a weighted average. The results

TABLE XVII

SECOND ORDER EXTINCTION CALCULATIONS

Stars	Date	k''_{bv}	Probable Relative Error	Relative Weight
θ_1,θ_2 Tau	3-1-69	0.127	6.95×10^{-2}	0.709
θ_1,θ_2 Tau	3-5-69	-0.0543	8.29×10^{-2}	0.429
θ_1,θ_2 Tau	3-28-69	0.0909	5.85×10^{-2}	1.000
α_1,α_2 Lib	4-6-69	0.615	8.72×10^{-2}	-----
α_1,α_2 Lib	5-11-69	0.141	4.97×10^{-2}	-----
	Average	0.0739	4.00×10^{-2}	

Stars	Date	k''_{ub}	Probable Relative Error	Relative Weight
θ_1,θ_2 Tau	3-1-69	0.0866	3.98×10^{-2}	1.000
θ_1,θ_2 Tau	3-5-69	0.0985	6.40×10^{-2}	0.387
θ_1,θ_2 Tau	3-28-69	0.251	10.7×10^{-2}	0.138
α_1,α_2 Lib	4-6-69	0.381	4.77×10^{-2}	-----
α_1,α_2 Lib	5-11-69	0.232	38.4×10^{-2}	-----
	Average	0.104	3.22×10^{-2}	

TABLE XVIII

FIRST ORDER EXTINCTION COEFFICIENTS

		K_v	K'_{bv}	K'_{ub}
3-1-69	θ_1 Tau	0.554	0.0813	-0.0909
	θ_2 Tau	0.590	0.0531	-0.00681
	Average	0.572	0.0672	-0.00851*
3-5-69	θ_1 Tau	0.543	0.110	0.0117
	θ_2 Tau	0.496	0.219	0.0785
	Average	0.519	0.165	0.0451
3-19-69	θ_1 Tau	0.263	0.0825	0.197
	θ_2 Tau	0.616	0.0911	1.35
	Average	0.267*	0.0868	0.390*
3-28-69	θ_1 Tau	0.281	0.0626	-0.0687
	θ_2 Tau	0.265	-0.0672	0.0247
	Average	0.273	0.0464*	0.00119*

*Weighted Average

TABLE XIX

PLEIADES DATA FOR 3-1-69

Star	Air Mass	v	(b-v)	(u-b)	v_o	$(b-v)_o$	$(u-b)_o$	$(V-v_o)$	V	B-V	U-B
η Tau	2.31	7.74	-0.762	1.98	6.66	-0.784	1.56	-3.80	2.86	-0.090	-0.330
27 Tau	2.14	8.63	-0.561	1.77	7.50	-0.616	1.39	-3.88	3.62	-0.085	-0.360
23 Tau	2.36	9.48	-0.549	1.79	8.23	-0.612	1.38	-4.07	4.16	-0.056	-0.430
17 Tau	2.59	9.11	-0.717	2.05	7.75	-0.754	1.52	-4.06	3.69	-0.107	-0.410
16 Tau	2.79	10.9	-0.858	2.21	9.44	-0.869	1.59	-3.99	5.45	-0.046	-0.330
19 Tau	3.06	9.95	-0.366	2.25	8.33	-0.489	1.56	-4.04	4.29	-0.106	-0.460
20 Tau	3.39	9.77	-0.523	2.38	7.98	-0.620	1.57	-4.12	3.86	-0.068	-0.400
18 Tau	3.84	11.6	-0.243	2.51	9.63	-0.432	1.54	-3.99	5.64	-0.075	-0.360

$K_v = 0.572$ $K'_{bv} = 0.0672$ $K'_{ub} = -0.00851$ $K''_{bv} = 0.0739$ $K''_{ub} = 0.104$

TABLE XX

PLEIADES DATA FOR 3-5-69

Star	Air Mass	v	(b-v)	(u-b)	v_o	$(b-v)_o$	$(u-b)_o$	$(V-v_o)$	V	B-V	U-B
η Tau	1.47	6.82	-0.593	1.63	6.06	-0.770	1.31	-3.20	2.86	-0.090	-0.330
27 Tau	1.51	7.55	-0.616	1.71	6.77	-0.795	1.38	-3.15	3.62	-0.085	-0.360
23 Tau	1.59	8.12	-0.565	1.71	7.29	-0.760	1.35	-3.13	4.16	-0.056	-0.430
17 Tau	1.81	7.68	-0.433	1.79	6.74	-0.673	1.37	-3.05	3.69	-0.107	-0.410
16 Tau	1.88	9.53	-0.527	2.31	8.55	-0.763	1.78	-3.10	5.45	-0.046	-0.330

TABLE XX (Continued)

Star	Air Mass	v	(b-v)	(u-b)	v_o	$(b-v)_o$	$(u-b)_o$	$(V-v_o)$	V	B-V	U-B
19 Tau	1.96	8.47	-0.651	1.83	7.46	-0.879	1.37	-3.17	4.29	-0.106	-0.460
20 Tau	2.01	8.11	-0.578	1.87	7.07	-0.823	1.39	-3.21	3.86	-0.068	-0.400
18 Tau	2.39	10.0	-0.344	2.20	8.75	-0.677	1.55	-3.11	5.64	-0.075	-0.360
21 Tau	2.57	10.3	-0.343	2.44	8.96	-0.700	1.67	-3.21	5.75	-0.044	-0.230

$K_v = 0.519$ $K'_{bv} = 0.165$ $K'_{ub} = 0.0451$ $K''_{bv} = 0.0739$ $K''_{ub} = 0.104$

TABLE XXI

PLEIADES DATA FOR 3-19-69

Star	Air Mass	v	(b-v)	(u-b)	v_o	$(b-v)_o$	$(u-b)_o$	$(V-v_o)$	V	B-V	U-B
η Tau	2.01	6.97	-0.693	1.65	6.43	-0.765	0.518	-3.57	2.86	-0.090	-0.330
27 Tau	2.10	7.71	-0.703	1.76	7.15	-0.776	0.555	-3.53	3.62	-0.085	-0.360
23 Tau	2.55	8.36	-0.627	1.78	7.68	-0.730	0.300	-3.52	4.16	-0.056	-0.430
17 Tau	2.71	8.01	-0.713	1.87	7.29	-0.805	0.286	-3.60	3.69	-0.107	-0.410
19 Tau	2.83	8.55	-0.632	1.82	7.80	-0.745	0.184	-3.51	4.29	-0.106	-0.460
20 Tau	3.06	8.19	-0.386	2.48	7.38	-0.564	0.495	-3.52	3.86	-0.068	-0.400

$K_v = 0.267$ $K'_{bv} = 0.0868$ $K'_{ub} = 0.390$ $K''_{bv} = 0.0739$ $K''_{ub} = 0.104$

TABLE XXII

PLEIADES DATA FOR 3-28-69

Star	Air Mass	v	(b-v)	(u-b)	v_o	$(b-v)_o$	$(u-b)_o$	$(V-v_o)$	V	B-V	U-B
η Tau	2.78	7.40	-0.547	1.97	6.64	-0.564	1.40	-3.78	2.86	-0.090	-0.330
27 Tau	3.30	8.26	-0.475	2.10	7.36	-0.512	1.38	-3.74	3.62	-0.085	-0.360
23 Tau	4.50	9.29	-0.315	2.53	8.07	-0.419	1.34	-3.90	4.16	-0.056	-0.430

$K_v = 0.273$ $K'_{bv} = 0.0464$ $K'_{ub} = 0.00119$ $K''_{bv} = 0.0739$ $K''_{ub} = 0.104$

TABLE XXIII

SCALE FACTORS

	ε	Probable Relative Error	Relative Weight
3-1-69	-0.857	1.75×10^{-2}	1.00
3-5-69	-0.459	1.15×10^{-2}	2.29
3-19-69	-0.0478	0.647×10^{-2}	7.27
3-28-69	-4.27	0.566×10^{-2}	9.50
Average	-2.00	0.390×10^{-2}	
	μ		
3-1-69	-0.0345	1.98×10^{-1}	1.32
3-5-69	0.0733	2.28×10^{-1}	1.00
3-19-69	0.135	1.40×10^{-1}	2.64
3-28-69	0.244	0.370×10^{-1}	37.9
Average	0.225	0.347×10^{-1}	
	ψ		
3-1-69	0.130	8.22×10^{-2}	1.50
3-5-69	0.265	10.1×10^{-2}	1.00
3-19-69	0.273	3.78×10^{-2}	7.07
3-28-69	1.38	8.97×10^{-2}	1.26
Average	0.381	3.03×10^{-2}	

are found in Table XXIII.

Summary of Results

The following values were determined:

k''_{bv} = 0.0739 Probable relative error = 4.00×10^{-2},

k''_{ub} = 0.104 Probable relative error = 3.22×10^{-2},

ε = −2.00 Probable relative error = 0.390×10^{-2},

μ = 0.225 Probable relative error = 3.47×10^{-2},

Ψ = 0.381 Probable relative error = 3.03×10^{-2}.

The iteration process for refining the scale factors was not carried out. Since that process is based on a relatively close match to the standard system ($\varepsilon \approx 0$, $\mu \approx 1$, $\Psi \approx 1$), it is not likely that it would converge starting with the values determined above. Certain undesirable features of the observational program, to be discussed in Chapter VI, are considered a possible source of the apparent calibration discrepancy.

CHAPTER VI

CONCLUSIONS

The principles of astronomical photometry have been applied to the problem of designing and placing in operation a photoelectric three color system. Certain mechanical problems, unique to the small telescope application, were encountered and successfully resolved. A short term observing program has provided preliminary values for local (Enid) second order extinction parameters. Scale factors (ε, μ, Ψ), the instrumental coefficients whose numerical values are strongly influenced by the structure of the pass bands of the natural color system, were also evaluated.

Thus, in a general observing program it would, in principal, be possible to transform from the Enid System to the system of Johnson and Morgan by use of Equations (4-16). This assumes, of course, that adequate extinction observations have been made so that the principal coefficients (K_v, K'_{bv}, K'_{ub}) and the zero-point terms (ζ_v, ζ_{bv}, ζ_{ub}) can be evaluated for the particular night in question. In this study, the scale factors were of primary interest, and the zero-point terms were not computed for any of the observing sessions, even though sufficient data was taken to do so.

Comparison of the derived scale factors with optimum values suggests a poor match between the Enid System and that of Johnson and Morgan. It is entirely possible, however, that part of the difficulty lies in shortcomings of the current observational program, rather than errors in the color system of the instrumentation. For this reason, it is suggested that calibration studies, using methods similar to those outlined in this paper, be carried out over a longer period of time (e.g., 6-9 months), in order that the operational characteristics of the Enid System can be better established. If, on the basis of such a study, it is shown that the match to the standard system is poor, then the filters must be changed to achieve a closer fit.

Certain undesirable features of the current observing program should be avoided, if possible, in future studies of this type. First, in a more leisurely calibration run, observing sessions can be selected with greater care than was possible in the present case. All four of the March nights were terminated by clouds rather than sunrise. On three of the six nights (two near March 4), the moon was near full phase. An exceptionally cloudy winter season prevented observation at more desirable times.

With one exception (March 5), cluster standards were observed under an air mass of 2.00 or larger. Of course, it is highly desirable that these stars be measured near zenith so that extinction effects will be minimized to a greater extent. Also, measures near zenith would avoid the large volume of noise from mercury vapor sources near the horizon. In the present case, weather and technical failures prevented cluster observations earlier in the season when the stars of interest were closer to zenith.

A final comment concerns choice of cluster standards. The Pleiades does not provide a very wide range of colors; i.e., most of the bright stars are class B. The Hyades and Coma Berenices clusters provide a broader color base than does the Pleiades cluster. The Praesepe, though it presents a rather broad range of colors, is somewhat too faint for the small telescope. Lack of reference material and poor sky position prevented effective observation of the Hyades in the present work; however, its' use is strongly encouraged in future calibration studies.

In conclusion, the principles of astronomical photometry have been discussed herein with the intent of implementing three color photoelectric work as an area of student participation at the secondary school level. The main design features of the Enid System appear adequate for the intended purpose. In particular, differential photometry of eclipsing variables is probably the most appropriate area of student activity at the present time. More extensive observations, of the type discussed in this paper, should be included in the total observational program in order to evaluate the quality of the match to the standard system.

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APPENDIX A

COMPUTER PROGRAMS

Two programs were used extensively to handle data. The DATA REDUCTION PROGRAM (TABLE XXIV) was also modified to produce observing lists for observatory use. The data lists (TABLES V through X) were produced by another slight modification of the DATA REDUCTION PROGRAM.

The LEAST SQUARES PROGRAM (TABLE XXV) is designed to fit a set of data points to a polynomial of any desired degree. The subroutine which solves the associated set of simultaneous equations corrects preliminary solutions for computer generated roundoff errors.

All programs used in this study were written in FORTRAN IV and were designed to run on the IBM/360 Mod 50.

TABLE XXIV

SOURCE PROGRAM FOR DATA REDUCTION

```
C THIS PROGRAM IS DESIGNED TO PROCESS PHOTOMETRIC DATA RESULTING FROM APPARENT
C BRIGHTNESS MEASURES IN THE UBV SYSTEM. STARS INCLUDED IN THE OBSERVATIONAL
C PROGRAM COMPRISE THE "STAR LIST."  FOR EACH STAR IN THE LIST, COORDINATE
C INFORMATION AND STANDARD MAGNITUDES AND COLORS ARE STORED.
C OBSERVATIONAL DATA, CONSISTING OF TIME OF OBSERVATION (GREENWICH MEAN TIME),
C RECORDER DEFLECTION (CORRECTED FOR SKY AND DARK CURRENT), AND AMPLIFIER
C SENSITIVITY ARE REDUCED TO YIELD AIR MASS, OBSERVED VISUAL MAGNITUDE AND
C COLOR INDICES: (B-V) AND (U-B).
C
C    INPUT FORMAT
C     "DIC" = DECIMAL IN CARD;  "NDP" = NO DECIMAL POINT
C      A) STAR LIST CARD - ONE FOR EACH STAR OBSERVED.
C         COLS.  1-3  ID NUMBER FOR STAR - NDP (I3)
C         COLS.  4-11 STAR NAME (A8)
C         COLS. 12-14 HOURS OF RIGHT ASCENSION - DIC OR F3.0
C         COLS. 15-17 MINUTES OF RIGHT ASCENSION -DIC OR F3.0
C         COLS. 18-21 SECONDS OF RIGHT ASCENSION -DIC OR F4.1
C         COLS. 22-25 ANNUAL PRECESSION IN RA (SEC/YR) - DIC OR F4.2
C         COLS. 26-28 DEGREES OF DECLINATION -DIC OR F3.0
C         COLS. 29-31 MINUTES OF DECLINATION -DIC OR F3.0
C         COLS. 32-34 SECONDS OF DECLINATION - DIC OR F 3.0
C         COLS. 35-38 ANNUAL PRECESSION IN DECLINATION - DIC OR F4.1
C         COLS. 39-43 EPOCH FOR COORDINATES -DIC OR F5.0
C         COL.  44-   BLANK,EXCEPT FOR LAST CARD OF STAR LIST WHICH HAS 1 HERE
C         COLS. 45-48 STANDARD VISUAL MAGNITUDE - DIC OR F4.2
C         COLS. 49-53 STANDARD (B-V) COLOR INDEX - DIC OR F5.3
C         COLS. 54-58 STANDARD (U-B) COLOR INDEX - DIC OR F5.3
C         COLS. 59-80 UNUSED
C
C THE STAR LIST MAY CONTAIN UP TO 50 STARS.
C
C      B) OBSERVATION SET
C       1) DATE CARD - ONE PER SET
C         COLS.  1-3  DAY OF MONTH (GMT) - NDP (I3)
C         COLS.  4-6  MONTH - NDP (I3)
C         COLS.  7-11 YEAR -NDP (I5)
C         COLS. 12-15 OBSERVER'S LATITUDE - DEGREES - DIC OR F4.0
C         COLS. 16-18 OBSERVER'S LATITUDE - MINUTES-DIC-ORF3.0
C         COLS. 19-21 OBSERVER'S LATITUDE - SECONDS - DIC OR F3.0
C         COLS. 22-24 SIDEREAL HOURS FOR 0 HOURS GMT - DIC OR F3.0
C         COLS. 25-27 SIDEREAL MINUTES FOR 0 HOURS GMT -DIC OR F3.0
C         COLS. 28-34 SIDEREAL SECONDS FOR 0 HOURS GMT - DIC OR F7.3
C         COLS. 35-44 GEOCENTRIC JULIAN DATE FOR 0 HOURS GMT - DIC OR D10.1
C         COLS. 45-49 EQUATION OF EQUINOXES - DIC OR F5.3
C         COLS. 50-52 OBSERVER'S WEST LONGITUDE - DEGREES - DIC OR F3.0
C         COLS. 53-55 OBSERVER'S WEST LONGITUDE - MINUTES - DIC OR F3.0
C         COLS. 56-58 OBSERVER'S WEST LONGITUDE - SECONDS - DIC OR F3.0
C         COLS. 59-78 UNUSED
C         COL.  79    1
C         COL.  80    1 EXCEPT FOR LAST SET TO BE PROCESSED. DATE CARD FOR
C                       FINAL SET BLANK IN COL 80.
C       2) OBSERVATION CARD - ONE FOR EACH OBSERVATION
C         COLS.  1-5  - BLANK
C         COLS.  6-8  - STAR LIST ID NUMBER OF STAR OBSERVED - NDP (I3)
C         COLS.  9-12 DEFLECTION FOR U READING (DECIMAL FRACTION OF FULL SCALE)
C                     DIC OR F4.3
C         COLS. 13-16 AMPLIFIER SENSITIVITY FOR U READING - DIC OR F4.2
C         COLS. 17-20 - DEFLECTION FOR B READING - SAME FORMAT AS COLS. 9-12.
```

TABLE XXIV (Continued)

```
C         COLS. 21-24 AMPLIFIER SENSITIVITY FOR B - SAME FORMAT AS COLS. 13-16.
C         COLS. 25-28 DEFLECTION FOR V READING - SAME FORMAT AS COLS. 9-12.
C         COLS. 29-32 AMPLIFIER SENSITIVITY FOR V READING - SAME FORMAT AS 13-16
C         COLS. 33-35 HOUR (GMT) OF OBSERVATION - DIC OR F3.0
C         COLS. 36-38 MINUTE (GMT) OF OBSERVATION - SAME FORMAT AS COLS. 33-35.
C         COLS. 39-41 SECOND (GMT) OF OBSERVATION - SAME FORMAT AS COLS. 33-35.
C         COLS. 42-43 BLANK
C         COL.  44    BLANK, EXCEPT LAST CARD OF SET CONTAINS 1.
C         COLS. 45-80 UNUSED
C
C INPUT SEQUENCE: STAR LIST CARDS, OBSERVATION SETS - EACH CONSISTING OF ONE (1)
C DATE CARD AND ONE OR MORE OBSERVATION CARDS.
C      NATURAL MAGNITUDES AND COLORS FROM OBSERVED BRIGHTNESS.
      DIMENSION RAH(50),RAM(50),RAS(50),ANVRA(50),DECD(50),DECM(50),DECS
     1(50),ANVDC(50),EPOCH(50),VMAG(50),BMVC(50),UMBC(50)
      REAL*8STAR(50)/50*0.0D+0/,DJ
  100 READ(5,101)  ID,STAR(ID),RAH(ID),RAM(ID),RAS(ID),ANVRA(ID),DECD(ID
     1),DECM(ID),DECS(ID),ANVDC(ID),EPOCH(ID),INDEX,VMAG(ID),BMVC(ID),UM
     2BC(ID)
  101 FORMAT(I3,A8,2F3.0,F4.1,F4.2,3F3.0,F4.1,F5.0,I1,F4.2,2F5.3)
      IF(INDEX.NE.0)GOTO110
      GOTO100
  110 WRITE(6,111)
  111 FORMAT('1',2X,'DATE',7X,'STAR',6X,'TIME (GMT)',4X,'RELATIVE AIR MA
     1SS',3X,'MAGNITUDE',7X,'COLOR',9X,'STANDARD VALUES'/' ',22X,'HR',2X
     2,'MIN  SEC                                  V         B-V      U-B
     3V         B-V      U-B')
      NDATE=0
  115 READ(5,116)MO,NDA,KYR,DLAT,TALM,SLAT,SH,SM,SS,DJ,EEQ,DLONG,DMLONG,
     1SLONG,NDATE,QUIT
  116 FORMAT(2I3,I5,F4.0,4F3.0,F7.3,D10.1,F5.3,3F3.0,20X,I1,I1)
      IF(NDATE.NE.0)GOTO120
      WRITE(6,117)
  117 FORMAT('0','DATE CARD MISSING')
      GOTO115
  120 NO=0
  121 CONTINUE
      OBS=0
      READ(5,123)OBS,NUM,DU,SNU,DB,SNB,DV,SNV,TH,TM,TS,FINISH
  123 FORMAT(I5,I3,3(F4.3,F4.2),4F3.0)
      NO=NO+1
      IF(STAR(NUM).NE.0)GOTO155
      WRITE(6,156)NUM
  156 FORMAT('0','NO ENTRY IN LIST FOR NUMBER ',I3,'.')
      GOTO121
  155 IF(OBS.EQ.0)GOTO125
      WRITE(6,124)NO
  124 FORMAT('0','CARD NUMBER ',I2,' FOLLOWING DATE CARD DOES NOT CONFOR
     1M TO OBSERVATION CARD FORMAT. DATA IGNORED.')
      GOTO121
C     BEGIN COORDINATE PRECESSION
  125 FACTR=(MO-1)/12.+NDA/365.+(KYR-EPOCH(NUM))
      DELD=FACTR*ANVDC(NUM)
      DELRA=FACTR*ANVRA(NUM)
      DSUM=ABS(DECD(NUM))*3600.+DECM(NUM)*60.+DECS(NUM)
      IF(DECD(NUM).GE.0.)GOTO130
      DSUM=-DSUM
  130 DSUM=DSUM+DELD
```

TABLE XXIV (Continued)

```
          RSUM=RAH(NUM)*3600.+RAM(NUM)*60.+RAS(NUM)+DELRA
      131 IF(RSUM.LT.8.64E+04)GOTO135
          RSUM=RSUM-86400.
      135 IF(ABS(DSUM).LT.3.24E+05)GOTO160
          IF(DSUM.LT.0.)GOTO140
          DSUM=6.48E+05-DSUM
          GOTO141
      140 DSUM=-6.48E+05-DSUM
      141 RSUM=RSUM+43200.
          GOTO131
C         COORDINATE PRECESSION COMPLETED. DECLINATION IS IN SECONDS OF ARC
C         AND RIGHT ASCENSION IN SECONDS OF TIME. THESE COORDINATES ARE NEXT
C         USED TO DETERMINE HOUR ANGLE AND ZENITH DISTANCE.
C         BEGIN SIDEREAL TIME COMPUTATION
      160 DELT=(TH*3600.+TM*60.+TS)*(1.+236.6/8.64E+04)
          CORLON=(((DLONG*3600.)+(DMLONG*60.)+SLONG)*24./360. )*(1.+(236.6/8
         1.64E+04))
          SIDT=SH*3600.+SM*60.+SS+DELT+EEQ-CORLON
          IF(SIDT.LT.8.64E+04)GOTO165
          SIDT=SIDT-8.64E+04
C         SIDEREAL TIME COMPUTATION COMPLETED.
C         BEGIN HOUR ANGLE AND ZENITH DISTANCE COMPUTATION
      165 HA=SIDT-RSUM
          IF(HA.GE.0.)GOTO170
          HA=HA+8.64E+04
      170 HARAD=HA*3.14159/4.32E+04
          DECRAD=DSUM*3.14159/6.48E+05
          RADLAT=(DLAT*3600.+TALM*60.+SLAT)*3.14159/6.48E+05
          SECZ=1./(SIN(RADLAT)*SIN(DECRAD)+COS(RADLAT)*COS(DECRAD)*COS(HARAD
         1))
          AIRMAS=SECZ-(1.8167E-03)*(SECZ-1.)-(2.875E-03)*((SECZ-1.)**2.)-(8.
         1083E-04)*((SECZ-1.)**3.)
C         SIDEREAL TIME, ZENITH DISTANCE, AND AIR MASS NOW FINISHED.
C         BEGIN COMPUTATION OF MAGNITUDES AND COLORS
          VMN=SNV-2.5*ALOG10(DV)
          BMVCN=(SNB-SNV)-2.5*ALOG10(DB/DV)
          UMBCN=(SNU-SNB)-2.5*ALOG10(DU/DB)
C         MAGNITUDES AND COLORS COMPLETE.
          NYR=KYR-1900
          NTH=TH
          NTM=TM
          NTS=TS
          WRITE(6,171)MO,NDA,NYR,STAR(NUM),NTH,NTM,NTS,AIRMAS,VMN,BMVCN,UMBC
         1N,VMAG(NUM),BMVC(NUM),UMBC(NUM)
      171 FORMAT('0',I2,'/',I2,'/',I2,3X,A8,3X,I2,3X,I2,3X,I2,9X,F6.3, 7X,F6
         1.3,6X,F6.3,2X,F6.3,5X,F6.3,6X,F6.3,2X,F6.3)
          IF(SECZ.LT.2.)GOTO175
          WRITE(6,172)
      172 FORMAT('+',T128,'*')
      175 IF(FINISH.EQ.0.)GOTO121
          WRITE(6,173)
      173 FORMAT('0','* STAR WITHIN 30 DEGREES OF HORIZON'/'1')
          IF(QUIT.NE.0)GUTO110
          STOP
          END
```

TABLE XXV

SOURCE PROGRAM FOR LEAST SQUARES ANALYSIS

```
      DIMENSION X(100),Y(100),Z(100),A(50,51),ANS(50),XTEMP(100)
C
C     LEAST SQUARES FIT OF AN NTH DEGREE POLYNOMIAL TO A SET OF DATA POINTS
C
C     INPUT
C     FIRST CARD COLS.  1- 2  DEGREE OF DESIRED POLYNOMIAL
C                             (NO DECIMAL POINT)
C     FOLLOWING CARDS COLS. 1-10  X VALUE
C                                 (DECIMAL IN CARD, CAN BE E FORMAT)
C                     COLS. 11-20  CORRESPONDING Y VALUE
C                                 (DECIMAL IN CARD, CAN BE E FORMAT)
C
C     LIMIT  100 PAIRS OF POINTS
C     TO INCREASE NUMBER OF POINTS CHANGE DIMENSIONS OF X,Y,Z,AND XTEMP AND
C     UPPER LIMIT OF DO LOOP AFTER STATEMENT 10 AND REPETITIVE SPECIFICATION IN
C     READ STATEMENT AFTER STATEMENT 15.
C
C     METHOD
C     SOLUTION OF THE N+1 NORMAL EQUATIONS PARTIAL M WRT A(J) FOR A(J)
C     (J=0,1,...,N) WITH A SUBROUTINE USING THE GAUSS ELIMINATION METHOD
C
1001  FORMAT(I2,/,(2E10.4))
1002  FORMAT(39H1COEFFICIENTS FOR ASCENDING POWERS OF X,//,(12X,E13.6))
1003  FORMAT(13H0DEVIATION = ,E13.6,/,40H PROBABLE ERROR OF SINGLE MEASU
     1REMENT = ,E13.6,//,32H - - - - - - -INPUT- - - - - - -,6X,10HCALCU
     1LATED,/,7X,1HX,17X,1HY,17X,1HY,//,(1X,E13.6,5X,E13.6,5X,E13.6))
1004  FORMAT(1H1)
1005  FORMAT(29H NO SOLUTION FOUND FOR MATRIX)
      DO 10 I=1,50
      DO 10 J=1,51
10    A(I,J)=0.
      DO 15 I=1,100
15    Z(I)=0.
      READ(5,1001,END=20)N,(X(I),Y(I),I=1,100)
20    NPTS=I-1
      NPLUS1=N+1
      NPLUS2=N+2
      A(1,1)=NPTS
      DO 30 I=1,NPTS
      XTEMP(I)=1.
30    A(1,NPLUS2)=A(1,NPLUS2)+Y(I)
      DO 50 I=2,NPLUS1
      DO 40 J=1,NPTS
      XTEMP(J)=X(J)*XTEMP(J)
      A(1,I)=A(1,I)+XTEMP(J)
40    A(I,NPLUS2)=A(I,NPLUS2)+XTEMP(J)*Y(J)
50    CALL PROP(A,1,I,I)
      NLESS1=N-1
      IF(NLESS1.EQ.0)GOTO73
      DO 70 I=2,N
      DO 60 J=1,NPTS
      XTEMP(J)=X(J)*XTEMP(J)
60    A(I,NPLUS1)=A(I,NPLUS1)+XTEMP(J)
70    CALL PROP(A,I,NPLUS1,NPLUS2-I)
   73 DO 75 J=1,NPTS
      XTEMP(J)=X(J)*XTEMP(J)
75    A(NPLUS1,NPLUS1)=A(NPLUS1,NPLUS1)+XTEMP(J)
      CALL SIMEQ(A,NPLUS1,ANS,ICC,50,51)
      IF(ICC.EQ.1)GO TO 90
      D=0.
      DO 80 J=1,NPTS
      Z(J)=Z(J)+ANS(1)
      DO 77 I=2,NPLUS1
77    Z(J)=Z(J)+ANS(I)*X(J)**(I-1)
80    D=D+(Y(J)-Z(J))*(Y(J)-Z(J))
      DEV=.6745*SQRT(D/(NPTS-1))
      WRITE(6,1002)(ANS(I),I=1,NPLUS1)
      WRITE(6,1003)D,DEV,(X(I),Y(I),Z(I),I=1,NPTS)
      WRITE(6,1004)
      CALL EXIT
90    WRITE(6,1005)
      CALL EXIT
      END
      SUBROUTINE PROP(A,L,M,N)
      DIMENSION A(50,51)
      LPLUSM=L+M
      LL=L+N-1
      LPLUS1=L+1
      DO 10 I=LPLUS1,LL
      J=LPLUSM-I
10    A(I,J)=A(L,M)
      RETURN
      END
```

TABLE XXV (Continued)

```
      SUBROUTINE SIMEQ(X,N,ANS,ICC,NO1,NO2)
C
C     SOLUTION OF AN NXN SYSTEM OF LINEAR ALGEBRAIC EQUATIONS USING THE
C     GAUSS ELIMINATION MEHTOD WITH REPEATED APPLICATION FOR IMPROVED RESULTS
C
C     USAGE
C     CALL SIMEQ(X,N,ANS,ICC,NO1,NO2)
C
C     PARAMETERS
C     X       SYSTEM (NXN+1)  STORED ONE EQUATION PER ROW
C     N       NO. OF VARIABLES +1
C     ANS        VECTOR TO CONTAIN ANSWERS
C     ICC        RETURN CODE
C                0    CORRECT SOLUTION (TO FOUR SIG. FIG.)
C                1    NO UNIQUE SOLUTION TO SYSTEM
C                2    SOLUTION NOT FOUND TO FOUR SIGNIFICANT DIGITS AFTER 5
C                     ITERATIONS
C     NO1        FIRST DIMENSION OF X (MUST BE SAME AT DIMENSION STATEMENT IN
C               CALLING PROGRAM)
C     NO2        SECOND DIMENSION OF X (MUST BE SAME AS DIMENSION STATEMENT IN
C               CALLING PROGRAM)
C
C     LIMIT
C     50 UNKNOWNS
C     TO CHANGE, CHANGE DIMENSIONS OF B,A,R AND NO1,NO2 IN CALL STATEMENT.
C     DIMENSION OF B,A,R MUST BE GREATER THAN OR EQUAL TO NO1
C
      DIMENSION X(NO1,NO2),B(50,51),A(50),R(50),ANS(NO1)
1001  FORMAT(1X,5E15.6)
      NPLUS1=N+1
      NPLUS2=N+2
      NLESS1=N-1
      INO=1
      ICC=0
      DO 6 I=1,N
      DO 6 J=1,NPLUS1
6     B(I,J)=X(I,J)
      DO 1000 KOUNT=1,5
7     DO 60 I=1,NLESS1
      K=I
      L=I+1
      DO 10 J=L,N
10    IF(ABS(X(K,I)).LE.ABS(X(J,I)))K=J
      IF(ABS(X(K,I)).LT.1.E-06)GO TO 300
20    IF(K.EQ.I)GO TO 40
      DO 30 J=1,NPLUS1
      TEMP=X(I,J)
      X(I,J)=X(K,J)
30    X(K,J)=TEMP
40    IF(X(I,I).EQ.1.)GO TO 50
      L=NPLUS1
      K=I+1
      DO 45 J=K,NPLUS1
45    X(I,J)=X(I,J)/X(I,I)
      X(I,I)=1.
50    KK=NPLUS2-I
      DO 60 JJ=1,KK
      J=NPLUS2-JJ
```

TABLE XXV (Continued)

```
      MM=I+1
      DO 60 K=MM,N
60    X(K,J)=-X(K,I)*X(I,J)+X(K,J)
      IF(ABS(X(N,N)).LT.1.E-06)GO TO 300
      IF(X(N,N).EQ.1.)GO TO 70
      X(N,NPLUS1)=X(N,NPLUS1)/X(N,N)
      X(N,N)=1.
      A(N)=X(N,NPLUS1)
      I=NLESS1
65    J=I+1
      A(I)=0.
70    A(I)=A(I)+X(I,J)*A(J)
      IF(J.EQ.N)GO TO 80
      J=J+1
      GO TO 70
80    A(I)=X(I,NPLUS1)-A(I)
      IF(I.EQ.1)GO TO 90
      I=I-1
      GO TO 65
90    IF(IND.EQ.1)GO TO 98
      DO 93 I=1,N
93    IF(ABS(A(I)).GT.ABS(ANS(I)/1.E+04))IND=1
94    DO 95 I=1,N
95    A(I)=ANS(I)-A(I)
98    DO 100 I=1,N
100   R(I)=0.
      DO 110 I=1,N
      DO 110 J=1,N
110   R(I)=R(I)+B(I,J)*A(J)
      DO 120 I=1,N
120   R(I)=R(I)-B(I,NPLUS1)
      IF(IND.NE.1)GO TO 500
135   DO 140 I=1,N
      ANS(I)=A(I)
      X(I,NPLUS1)=R(I)
      DO 140 J=1,N
140   X(I,J)=B(I,J)
      IND=2
1000  CONTINUE
      ICC=2
      GO TO 500
300   ICC=1
500   RETURN
      END
```

VITA

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