No. 14. A COMPLETELY DIGITIZED MULTI-COLOR PHOTOMETER

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ABSTRACT

A completely digitized multi-color photometer has been built at the University of Texas and the University of Arizona. This device, which makes photometric observations in nine wavelength bands ranging from 0.35 to 5μ, records on a punched paper tape all of the data that are necessary for the complete reduction procedure. A complete reduction program suitable for electronic computers such as the CDC 1604 or the IBM 7090 has been written and used for the reduction of more than 3000 observations taken with the photometer. A description of the photometer and the reduction program is given in this paper.

1. *Introduction*

Approximately two years ago, we began, with the financial support of the National Science Foundation, a project to develop infrared photometric apparatus and to use the apparatus to make astronomical observations. This project has proceeded to the point at which a description of the apparatus that has been developed is in order. Already two papers (Borgman and Johnson, 1962; Johnson, 1962*a*) containing data taken with the new photometric apparatus have been published.

The recent development of infrared detectors having relatively high sensitivity has made it possible to consider stellar photometry at wavelengths much longer than 1μ. Probably the first such photometry, at a wavelength of approximately 2μ, was that of Whitford (1948, 1958), who measured reddened and unreddened early-type stars and interpreted his data in terms of the law of interstellar reddening. Fellgett (1951) measured various bright stars of different spectral types. Hiltner (Strömgren, 1956) has used a PbS photometer to measure the polarization of highly reddened stars at the long wavelengths.

All of these observers used PbS cells and broadband filters (or no filter at all) which isolated wavelength bands whose effective wavelengths ranged from 1.5 to 2μ. Recent developments in detectors and filters, however, have made possible a refinement and extension of the observational procedures. Interference filters for the isolation of any desired wavelength band are not available, and a new detector, the InSb photovoltaic cell, has good sensitivity to wavelengths as long as 6μ. Recently, Mitchell and Barnhart (Slettebak, 1961) have also begun infrared stellar photometry using modern techniques and equipment.

For observation at wavelengths longer than 1μ, four bands centered at approximately 1.3, 2.2, 3.6, and 5.0μ were selected; the magnitudes obtained by observation at these wavelengths are designated *J, K, L,* and *M,* respectively. Since the value of observations at these long wavelengths would be enhanced considerably by observations of the same objects at shorter wavelengths, we have included in this photometer filters and photomultipliers for observation on the *UBV* system of Johnson and Morgan (1953) and on an *RI* system similar to that of Kron, White and Gascoigne (1953). In order to insure the maximum efficiency for observations in each of the nine wavelength bands, we have constructed three different photometers and amplifiers, using four different detectors.

The maximum efficiency in observation and data reduction will be obtained from automatic data recording and reduction procedures. Accordingly, this photometer has been designed and constructed to

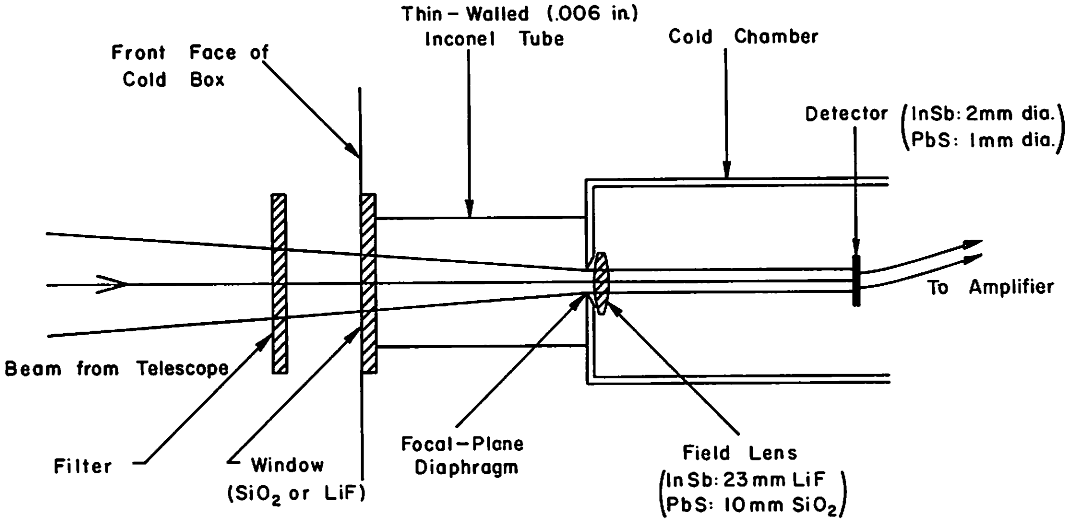

Fig. 1. The general design of the infrared photometer.

record on a punched paper tape all of the data that are needed for the complete reduction of the observations. This punched tape is fed into an electronic computer, which makes all decisions regarding the reduction of the data. The output data, after reduction to the standard system, are printed for examination by the operator and are also punched on IBM cards, one for each observation. After further analysis, all handled in the computer, the final data are printed by the electronic computer in a form suitable for publication.

2. *The Three Photometers*

(a) *The UBVRI Photometer*

The *UBVRI* photometer is a modification of an existing *UBV* photometer. The modification consists of substituting for the 1P21 cold box a two-phototube box. An RCA 1P21 is used for the *UBV* observations, and a modified ITT FW-118 (0.3-inch cathode diameter instead of the standard 0.1-inch) for the *RI* observations. A beam-switch for switching the light and electrical connections to one or the other of the two tubes is placed between the filter box and the two-cell cold box. The *UBV* section is sufficiently sensitive to measure stars as faint as 22d mag. with the 82-inch telescope (cf. Johnson and Sandage, 1956). The *RI* section will measure stars down to about $R = 18$ with the 82-inch telescope.

(b) *The IJK Photometer*

The highest sensitivity in the spectral range from 1μ to 3μ is obtained from PbS photoconductive cells. Accordingly, the *IJK* photometer was designed around this type of detector.

At the longest wavelengths to which PbS cells are sensitive, thermal radiation noise from the 300°K surroundings is appreciable, and a decrease in cell noise can be obtained by enclosing the PbS cell as completely as possible in a box maintained at dry ice temperature. The PbS cold box, therefore, has been constructed with the focal-plane diaphragm and the field lens inside the cold chamber. The PbS cell has an area of 1 mm^2; the fused quartz field lens, a focal length of 10 mm and a diameter of 4 mm; and the focal-plane diaphragm, a diameter of 3 mm. The image of the telescope mirror on the PbS cell is approximately 0.7 mm in diameter for a focal ratio of 13.5 and remains essentially fixed on the cell regardless of the position of a star in the diaphragm. Thus, this construction not only increases the signal-to-noise ratio of the PbS cell, but also allows the use of a cell with a smaller area than that of the focal-plane diaphragm. The general principles of this construction are shown in Figure 1.

The construction of the cold box and the associated guider box is shown in Figure 2. The chopper motor is a special Kollsman 1800 rpm synchronous motor, which has the property of maintaining shaft orientation within ± 2° of the phase of the 60 cps motor voltage; thus, the phase of the chopper blades with respect to the synchronous (phase) detector in the amplifier is maintained precisely. The amplifier consists of a pre-amplifier, having a voltage gain of 100 and tuned to 60 cps, mounted on the back of the cold box; an AC section with gain variable by

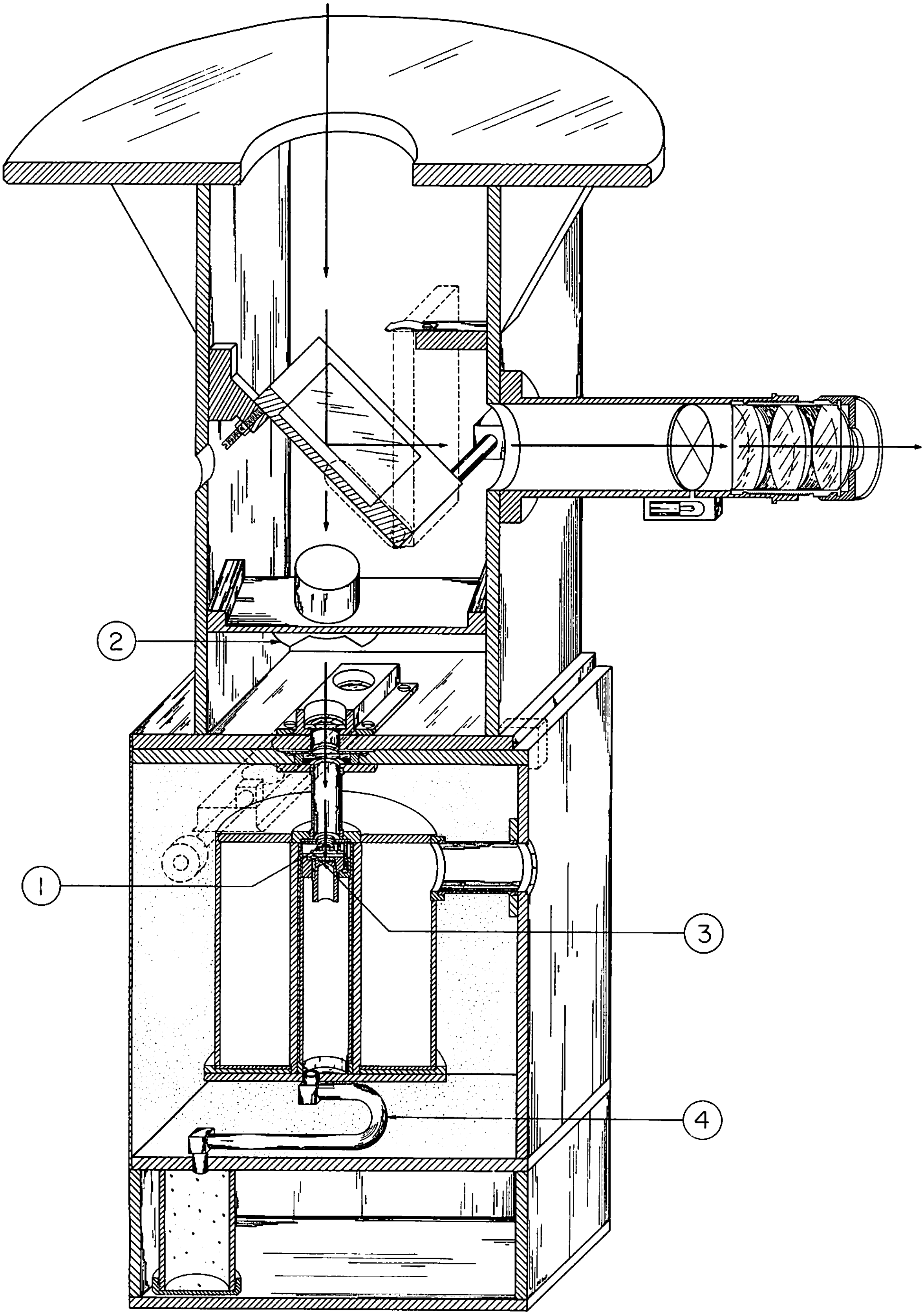

Fig. 2. The *IJK* photometer. In this diagram the numbered parts are as follows: *1* = the field lens and focal-plane diaphragm; *2* = the chopper; *3* = the PbS photoconductive detector; and 4 = the rubber hose leading to the drying agent (for preventing water from entering the inner refrigerated space). The mirror for reflecting the light to the guiding eyepiece is seen above the chopper motor; the filters and cold-box window are seen in this order between the chopper and the field lens.

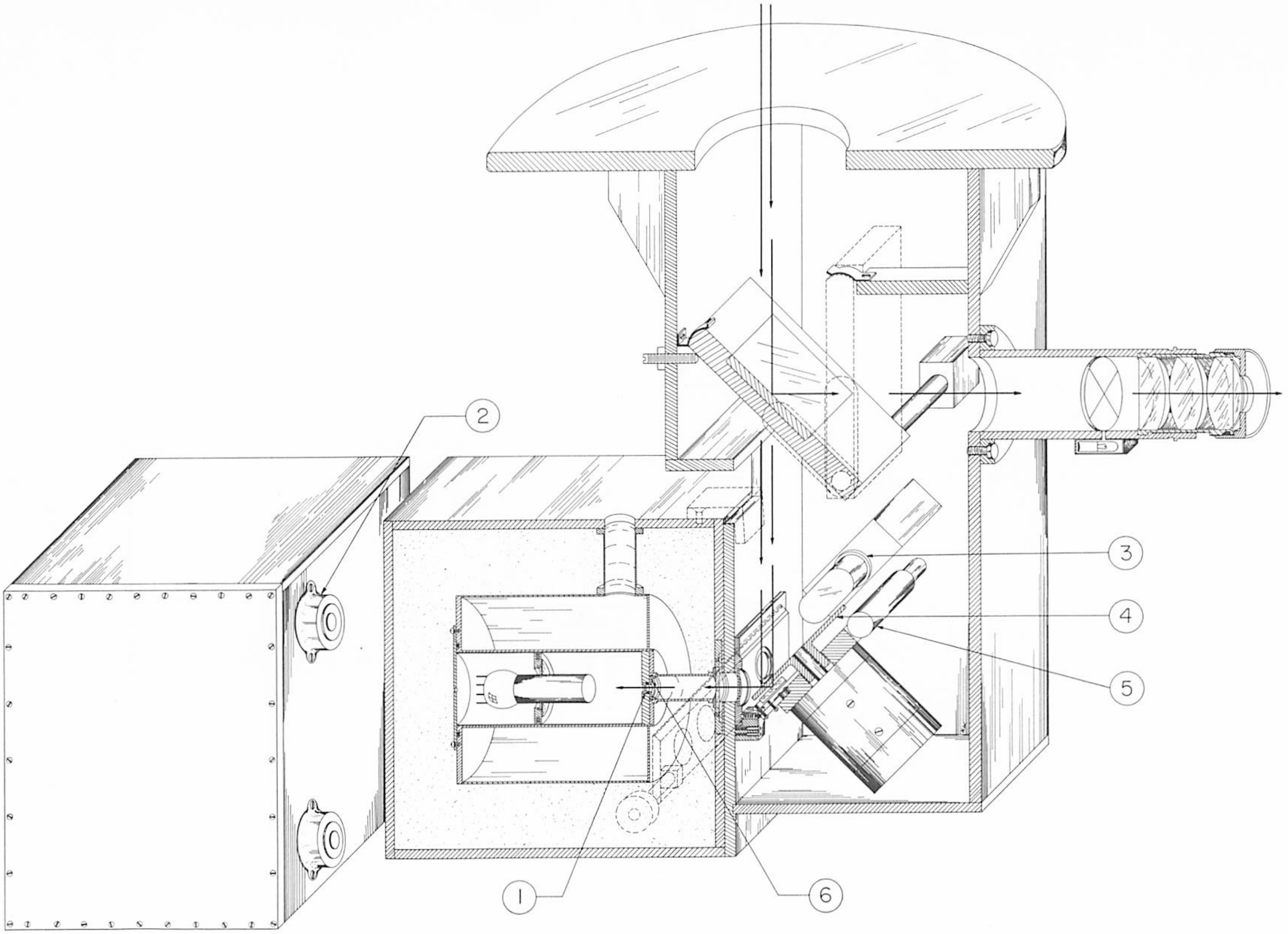

Fig. 3. The *JKLM* photometer. In this diagram the numbered parts are as follows: *1* = the field lens; *2* = the preamplifier shock mounts; *3* = the synchronizer photocell; *4* = the chopper; *5* = the synchronizer light source (which shines onto the photocell, through the chopper blades, *4*, producing pulses for synchronizing the AC amplifier); and *6* = focal-plane diaphragm. The construction of the *JKLM* photometer is similar to that of the *IJK* photometer. The principal differences are due to the necessity of chopping between the star and an immediately adjacent sky region, which is accomplished by the right-angle reflection alternately from the chopper blades and the adjacent mirror.

factors of 10 from 1 to 100; a synchronous (phase) detector; and a DC amplifier with its gain variable in 0.50 mag. steps over a range of 2½ mag. (a factor of 10). These AC and DC sections are built into a small box which is mounted on the telescope (as is the DC amplifier of the *UBVRI* photometer) in a convenient position near the photometer.

The sensitivity of the *IJK* photometer is sufficient to measure stars fainter than $K = 8.5$ with the 82-inch telescope.

(c) The JKLM Photometer

At a wavelength of 5μ (magnitude *M*), the highest sensitivity is obtained with an InSb photovoltaic detector cooled to the temperature of liquid nitrogen (77°K). As in the case of the PbS cold box, and for the same reasons, the InSb detector is completely enclosed within a chamber submerged in the refrigerant. Since the InSb detector is strongly temperature sensitive, the box in which it is enclosed is made of heavy copper; this eliminates short-time temperature changes and improves the stability of the detector. Its stability is quite satisfactory and its signal-to-noise ratio is improved by a factor of approximately 5, compared with operation exposed to 300°K radiation.

The InSb detector, manufactured by Texas Instruments, Inc., has a sensitive area 2 mm in diameter; accordingly, the field lens, made of LiF, has a focal length of 23 mm and a diameter of 8 mm. Again, the focal-plane diaphragm has a diameter of 3 mm, corresponding to approximately 22 inches at the Cassegrain focus of the 82-inch telescope.

At the longer wavelengths of 3.6μ and 5μ (magnitudes *L* and *M*), the radiation from the chopper, at a temperature of 300°K, is so much greater than that received from the sky that it swamps the signals from faint stars. In fact, during the first observations at 3.6μ (Johnson, 1962*a*), the chopper signal, which at that time had to be balanced out within the amplifier, was more than 3000 times the signal from the faintest star that was measured.

This chopper signal can be largely canceled out by reflecting the starlight and an adjoining sky region alternatively from the chopper and a fixed mirror; this construction minimizes the temperature difference between the two views seen by the detector. The construction of the *JKLM* photometer is shown in Figure 3. Note the right-angle bend of the light beam upon reflection from the mirror and chopper blades.

The chopper has nine blades and rotates at approximately 9000 rpm, producing a chopping frequency of 1450 cps. As in the PbS photometer, a pre-amplifier, tuned to the chopping frequency of 1450 cps, is mounted on the cold box. The InSb cell has a very small voltage output compared with the PbS cell, however, and the pre-amplifier gain is very high; it is therefore necessary to shock mount the pre-amplifier to isolate it from the chopper motor vibration.

The main amplifier is virtually identical to that used in the PbS photometer, the principal differences being due to the chopping frequency of 1450 cps. In addition to this amplifier there is a photoelectric pick-up of the chopper frequency and phase. The voltage from this photoelectric pick-up is fed to a frequency determining circuit that stabilizes the chopper motor speed and is also used to synchronize the synchronous detector with the chopper blades.

The sensitivity of the *JKLM* photometer is such that it can measure stars as faint as approximately $K = 5.5$ with the 82-inch telescope.

(d) The Filter Transmissions

The measured transmissions of the filters used for the magnitudes *U, B, V, R, I, J, K,* and *L* are shown in Figure 4, plotted against $1/\lambda$. The approximate effective wavelengths for these filter bands are listed in Table 1. The *U, B, V* filters have been described by Johnson (1955, 1962*b*); the *R, I, J, K,* and *L* filters were made by the Optical Coating Laboratories (Santa Rosa, California) or by Infrared Industries (Waltham, Massachusetts).

TABLE 1
Effective Wavelengths

Magnitude System	Effective Wavelength, Microns
U	0.35
B	0.44
V	0.55
R	0.70
I	0.88
J	1.25
K	2.20
L	3.6

3. *The Digital Recorder*

The digital recording portion of the photometer serves to record the observational data in a form

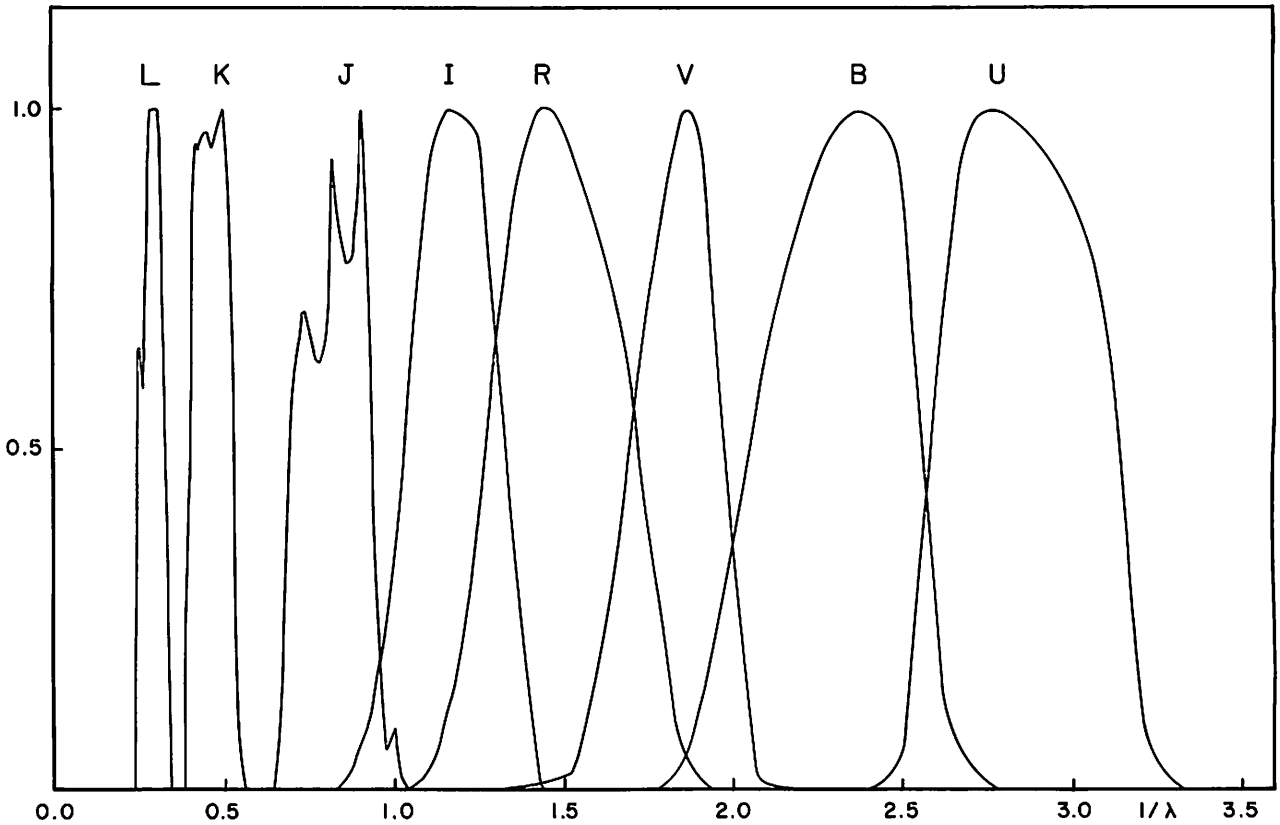

Fig. 4. Percentage of maximum sensitivity for the several magnitude systems. Filter transmission, detector sensivities, and mirror reflectivities are all included.

suitable to be fed directly into an electronic computer. It has the following components: (a) the paper tape punch; (b) the control circuits; (c) the integrator and timers; (d) the digital voltometer; (e) the card reader; (f) the digital clock and calendar; and (g) the power supplies. These components are sufficient to record all of the observational data required for the complete reduction of the photometric observations. A short description of each of the components follows.

(a) The paper tape punch is a seven-level Friden punch, used without modification.

(b) The control circuits contain the stepping relays for sequential recording of the data in the order required by the computer program, the coding relays for the seven-level punch code, and the push-buttons and switches used by the observer to initiate various parts of the operating cycle.

(c) The integrator is essentially the same as that of Gardiner and Johnson (1955), but with control relays and associated circuitry to adapt it to the present application. Two integration times, selected by the observer, are available: 120 sec. and 15 sec.

(d) The digital voltometer is a self-balancing potentiometer similar to that of the Minneapolis-Honeywell Brown recorder familiar to astronomers; it does in fact use some of the components of the Brown recorder. This self-balancing potentiometer turns the shaft of a Coleman Electronics Co. four-place digitizer, the output of which is displayed by an electronic read-out on the front panel of the unit and simultaneously punched on the paper tape.

(e) In order to make the operation of this apparatus as simple and error-proof as possible, we have included a twenty-column card reader. The observing card for each object is a punched IBM card which when inserted into the card reader causes to be recorded on the paper tape the name (or number) of the object and its position (right ascension and declination).

(f) The time of each observation is automatically recorded from the digital clock and calendar. This device has switch closures for each year, month, day, hour, and minute from the year 1960 through the year 1969.

(g) The power supplies provide regulated power for all of the components of the photometer.

A photograph of the digital photometer is shown

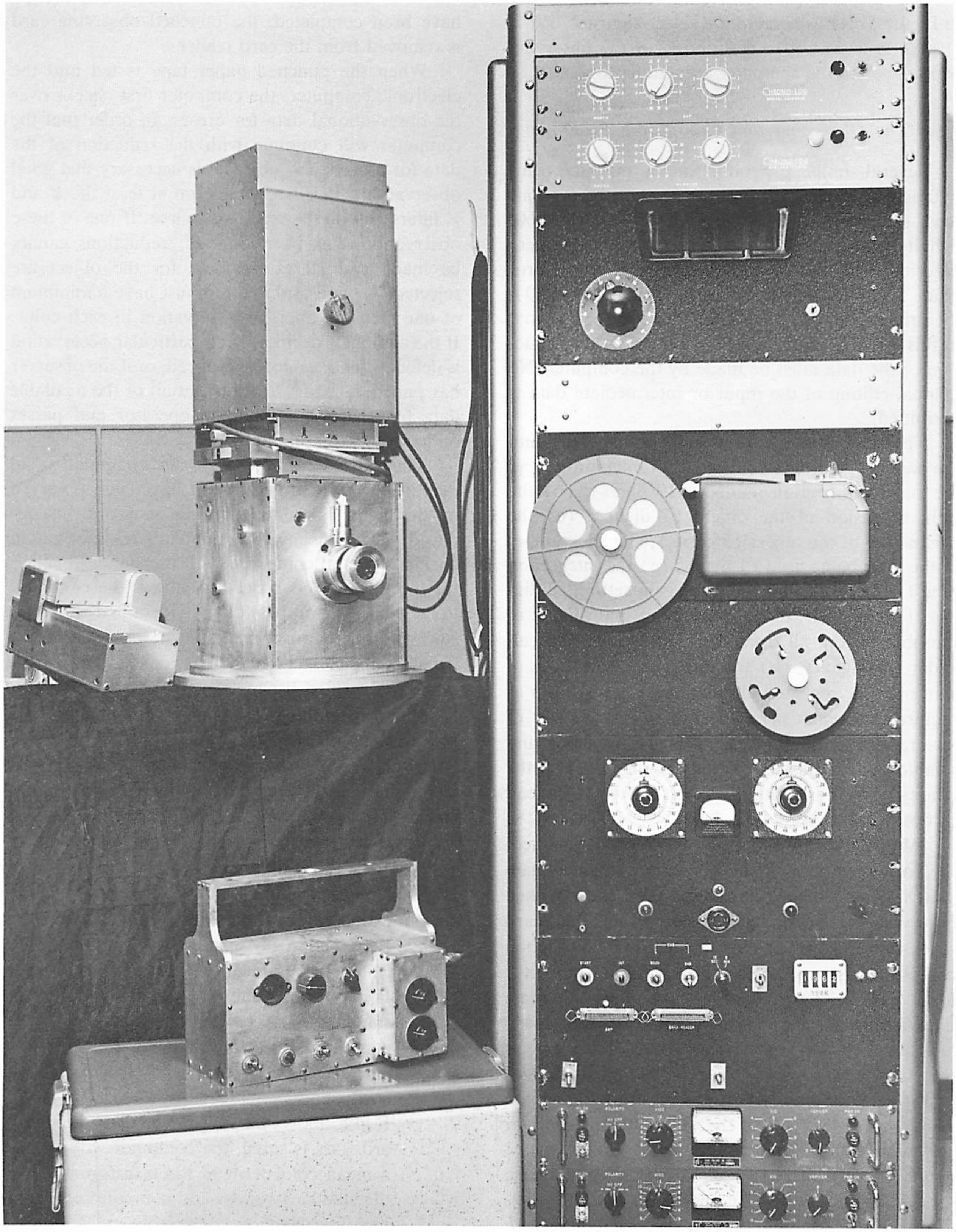

Fig. 5. Digital photometer components. The digital clock and calendar are at the top, the digital voltometer and electronic read-outs just below, the Friden tape punch in the center, the integrator and timers just below the tape punch, the control circuits just below, and the two high-voltage power supplies at the bottom. Other power supplies are on the integrator and control circuit chasses. The DC amplifier is on the box at the lower left; the card reader and photometer are on the table to the left above the amplifier.

in Figure 5. It has been in use since August 2, 1961.

We now pass to a description of the observing procedure and the computer reduction program.

4. The Observing and Computing Program

Several similar programs for the machine computation of astronomical photoelectric observations have been published (Arp, 1959; Mitchell, 1960; Schulte and Crawford, 1961), and we will not here describe our program in detail. In general, the program follows that described by Mitchell (1960), the principal modifications being due to the fact that in this application all decisions regarding the reduction of the data must be made by the computer. No manual editing of the input or intermediate data is permitted.

The data that are punched automatically into the paper tape by the digitized photometer are: (a) the star identification number (10 digits); (b) the right ascension of the object (5 digits); (c) the declination of the object (5 digits); (d) the number of the filter being used (1 digit); (e) the integration time (1 digit); (f) the amplifier gain setting (2 digits); (g) the year, month, day, hour and minute of the observation, all from the digital clock and calendar (10 digits); (h) the integrated deflections of star and sky, repeated alternately as many times as required (4 digits per deflection); (i) the end of integrations symbol (2 digits); (j) the hour and minute at end of observation (4 digits); (k) the quality of the observation (1 digit); and (l) the end of observation symbol (1 digit).

After the star or other object has been identified, the correct settings of the filter disc, amplifier gain switches, etc., have been found, and the punched observing card has been inserted into the card reader, the "start" button is pushed. This action causes the first seven items of data above (34 digits) to be punched into the paper tape. Next, alternate integrations of star and sky deflections are made and punched into the tape until the observer feels that sufficient precision has been obtained. In general, two 15-second deflections on the star and one 15-second deflection on the sky suffice except for the fainter stars. The observer now pushes one of two buttons labeled "good" or "bad" to indicate the end of the observation and its quality. He resets the filter disc, amplifier gain, etc., as required for the next observation and repeats the procedure. When all of the observations on a particular object have been completed, the punched observing card is removed from the card reader.

When the punched paper tape is fed into the electronic computer, the computer first checks over the observational data for errors. In order that the computer will continue with the reduction of the data for a particular object it is necessary that good observations have been made on at least the B and V filters and on the standard source. If one of these observations has been omitted, reductions cannot be made and all of the data for the object are rejected. A good observation must have a minimum of one star and one sky observation in each color. If the computer decides that a particular observation is defective and cannot be reduced, or if the observer has punched "bad," it prints out all of the available data for examination by the operator and passes on to the next observation.

The next step taken by the computer is to identify the standard stars that have been observed on the night. The data for these stars are then reduced, using mean extinction and transformation coefficients, and compared with the standard values for these stars; this procedure allows the computer to reject observations of mis-identified standard stars and other errors made by the observer before it enters the next stage of the reduction program. After the verified list of standard-star observations has been assembled, such nightly extinction and transformation coefficients as can be determined from the available data are computed. The coefficients that will be computed under various circumstances are as follows:

a. If at least four standard stars whose colors are widely different were observed over a large range in air mass, individual nightly extinction and transformation coefficients to the standard system will be computed (cf. Mitchell, 1960).

b. If in *a*, above, the range in air mass for the standard-star observations was small, the computer will assume a mean extinction coefficient and compute nightly transformation coefficients.

c. If in *a*, above, the range in color of the standard stars is small, the computer will assume a mean color-term in the transformation to the standard system and compute individual nightly extinction coefficients.

d. If both the range in air mass and the range in color-index of the standard stars are small, the computer will assume mean extinction coefficients and transformation color-terms and compute systemic zero-points only. A minimum of two observations on at least one standard star is required for this operation.

e. If only one observation on only one standard star was obtained on a given night, or if no standard star was observed at all, the computer will assume mean values for all coefficients and zero-points. The reduced values from this last operation are printed out for examination by the operator, but are not listed among the final data. (We assume that a night on which only one observation was obtained on only one standard star must have been so poor that a special decision to include the data must be made.)

After the extinction and transformation coefficients have been computed (or assumed), all of the observations taken on a given night, including standard star observations that were rejected earlier, are reduced. The Julian date and the sidereal time are computed from the standard time of observation; the hour angle, from the sidereal time and the right ascension of the object; and the air mass, from the computed hour angle of the observation and the declination of the object (the latitude and longitude of the observatory are known, of course).

At this point the computer has determined the Julian dates, and the magnitudes and color-indices transformed to the standard systems, for each of the good observations on a night. These data are now printed for examination by the operator and are punched into IBM cards for further analysis. Such additional analysis may consist of the collection (in the computer) of all of the observations on each individual object and the printing out of the mean values in a form suitable for publication; the table of values for the α Per cluster (Mitchell, 1960) was made in this fashion.

The reduction program has been written for both a CDC 1604 and an IBM 7090. When the CDC 1604 is used, the paper tape is fed directly into the computer; with the IBM 7090 it is necessary to run the tape through an IBM 047 tape-to-card converter before the 7090 will accept the data. Typical run times in the computers (5 nights of 5-color data) are 4.5 minutes for the CDC 1604 and 0.7 minutes for the IBM 7090.

5. *Summary*

The program for the development of infrared photometric apparatus has so far produced the equipment that is described in this article. Development is being continued, and we expect before long to have even more sensitive apparatus. The present photometer has, however, already been used to make significant astronomical observations, and we are beginning a new program for the *UBVRIJK* observations of the 1000 brightest stars. The success of these programs has been dependent upon the development of the fully digitized multi-color photometer.

We are indebted to Mr. William Buzbee for programming the CDC 1604 in machine language and in Fortran. We are also indebted to the Western Data Processing Center of the University of California at Los Angeles for the use of the IBM 7090 (such use took place after the move of the authors to the University of Arizona). This development has been supported in part by the National Science Foundation under Grants G-8164, G-14977 (to the University of Texas) and G-21970 (to the University of Arizona).

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