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A Computer-Controlled Photometric Telescope

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A description of the automatic telescope currently in operation at the Pine Bluff Station of the Washburn Observatory is given. The telescope is an 8-in. reflector feeding an automatic photoelectric photometer on a digitally driven equatorial mounting. The telescope system is under the control of a PDP-8 general-purpose digital computer. The programming provides for setting on the stars, whose positions are stored in the memory, carrying out the photometric measurements and processing the data in real time. The system is used primarily as an extinction telescope.

I. INTRODUCTION

THE careful determination of atmospheric extinction, sky brightness, and quality of the sky are a necessary but time-consuming part of any photometric program. Indeed, it has been said that a photometric observer has the choice of doing astronomical research or measuring atmospheric extinction, but not both. In any event it has long been recognized that the use of auxiliary instruments such as Polaris photometers and sky brightness meters can substantially increase the efficiency and quality of observations. The present paper describes an automatic telescope, which makes multicolor observations of standard stars throughout the night, and provides real time computation of extinction coefficients. The telescope is part of a program of instrument development initiated at the Washburn Observatory to increase the quality, versatility, and efficiency of photometric observations. The techniques employed have resulted in approximately doubling the number of nights on which useful spectrophotometric results may be obtained, and in more effectively utilizing this observing time. The techniques described here are, of course, applicable to the operation of larger telescopes for routine observing (cf. Maran 1967).

The automatic telescope is under the control of a general-purpose digital computer that accepts stellar positions entered on punched paper tape. After completing a search and centering routine the telescope and associated photometer carries out a series of multicolor filter measurements, storing the data in the control computer for further processing. This sequence of measurements continues automatically throughout the night until, under program control, the telescope is shut down at dawn.

The following sections describe the telescope, the control circuitry, the programming, and observational results.

II. TELESCOPE AND PHOTOMETER

The instrument is similar to one of the telescopes developed for the Wisconsin Experiment Package as a part of the Orbiting Astronomical Observatory. As

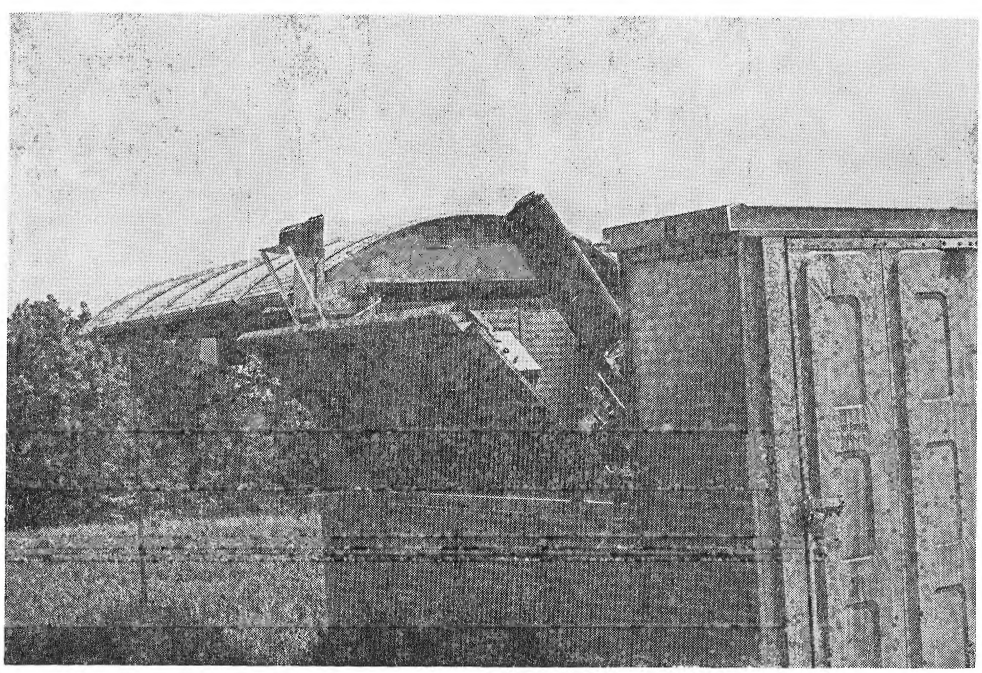

FIG. 1. The housing for the automatically controlled 8-in. telescope. The roof and side flaps are opened under computer control and closed automatically when rain is detected or wind or sky brightness exceeds programed limits.

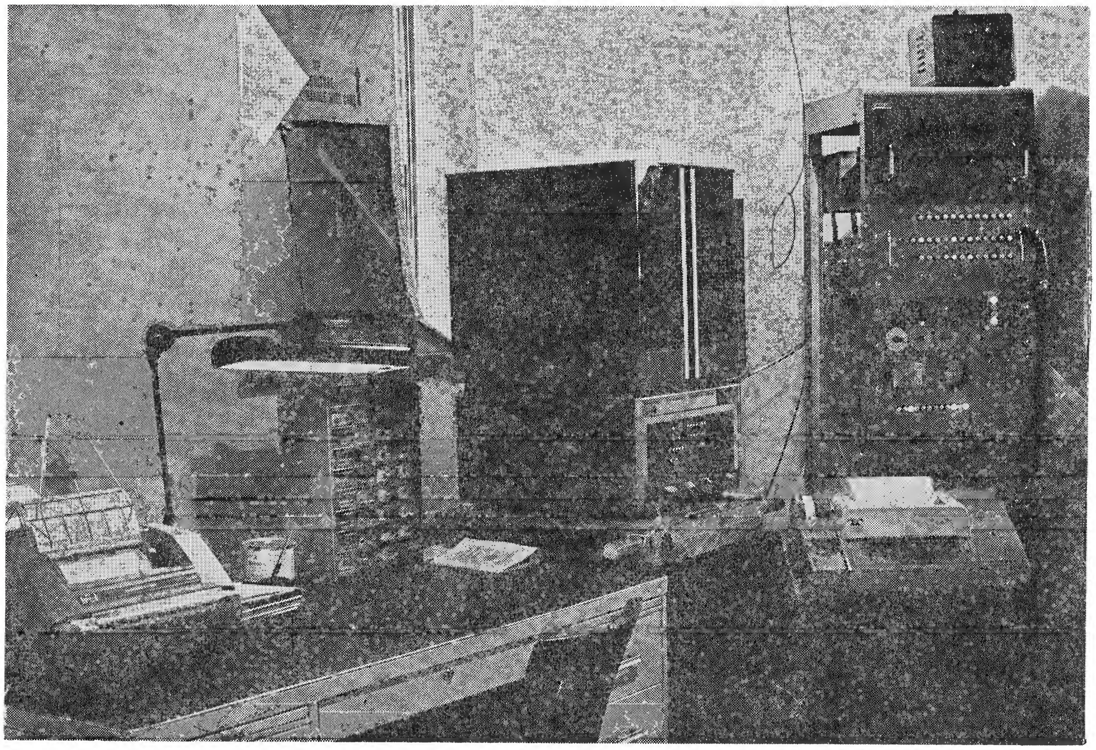

FIG. 2. The telescope control room, showing from left to right: Kleinschmidt Teleprinter on desk, PDP-8 computer, system electronics, and Teletype.

such the automatic telescope is a good example of the so-called "spinoff" of the space program that directly benefits ground-based astronomy.

The telescope is an 8-in., $f/4$ reflector, utilizing an off-axis parabola. The photoelectric photometer is mounted at the upper end of the tube. Solenoid-operated diaphragms of 10 and 2 min of arc are located in the focal plane. Immediately behind the entrance diaphragm is a five-position filter wheel operated by a stepper motor. This filter wheel contains a set of U, B, V filters, an interference filter and a Čerenkov standard source for sensitivity calibration. A Fabry lens images the telescope objective on the photocathode of an EMI 6256B photomultiplier. The output of the photomultiplier is fed to a dc amplifier and to a pulse preamplifier and scaler located on top of the telescope tube. This provides both a digital and an analogue output simultaneously. The gain of the dc amplifier and the pulse counter exposure time are under computer control, as are the filter wheel positions and diaphragm selection.

The polar and declination axes of the equatorial telescope mount are driven by stepper motors with shaft encoders to measure the position of the instrument. The telescope is located about 100 yards northwest of the Pine Bluff Observatory main building in a small metal shed with electrically operated roof and side walls. The computer and control consoles are located in the basement of the main building. Figures 1 and 2 show the telescope housing, mounting, and control console.

III. CONTROL CIRCUITRY

A block diagram of the extinction telescope system is given in Fig. 3.

The heart of the system is a PDP-8 computer with a memory of 4096 12-bit words and a minimum instruction set. To this has been added an analogue-to-digital converter and an eight-channel multiplexer for digital status. The V/D converter allows the computer to sample the photomultiplier signal; and the multiplexer provides 96 bits of binary status information describing such things as position of the telescope, sidereal time, photometer status, and digital data. Commands are provided to operate external devices using the pulse-generation capability of the computer.

There are separate computer commands to drive the stepper motors one step in any direction, enable the hour angle drive, and operate either of two external controls. The Teletype printer has been replaced with a Kleinschmidt M-311 printer for heavy-duty use (Miedaner and McNall 1967).

The controls are designed to perform functions that could be handled by a computer program. This simplifies programming of these functions, and eases the core storage requirements on the small computer. Each control is operated with a special command, and derives

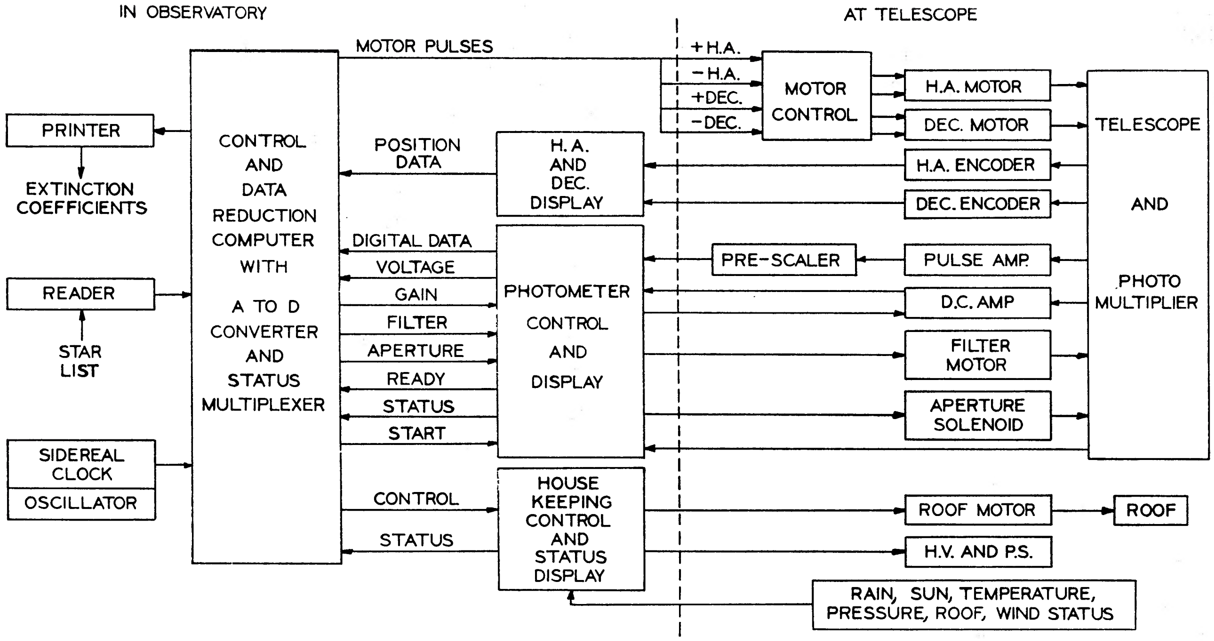

FIG. 3. Extinction telescope system functional block diagram.

its information from the contents of the 12-bit accumulator register in the computer.

The housekeeping control performs only switching functions; turning on or off any I/O devices, telescope drive power, and the photomultiplier high-voltage supply; opening and closing the roof, and switching the analogue inputs.

The photometer control provides the operation of the photoelectric photometer itself. On the computer start command it will set the desired filter, aperture, and gain (or exposure time). Photometer status and a "ready" signal are supplied to the computer when the reading has been made and the amplifier has settled. Data are then available as a dc voltage and a digital count.

Positioning of the instrument is accomplished through four devices: the stepper motor control, hour-angle drive, position encoders, and sidereal clock. The motor control provides power and pulses to step the polar or declination motors in either direction upon receipt of the appropriate computer command. Each such command will result in one step only, allowing speed to be controlled by the computer. The exception to this technique is the hour-angle drive, which provides a sidereal rate continuously, when activated.

Position of the instrument is monitored by a Datex shaft position encoder on each axis. These furnish position data to seconds of time in hour angle and 6 sec of arc in declination for a display as well as for the computer. An Astrodigit sidereal oscillator drives a counter and display that can also be read by the computer, allowing computation of hour angle position from the right ascension.

IV. PROGRAMING

A considerable portion of the programing effort was purely of an experimental nature, since the capabilities and limitations of the equipment were uncertain. Programing philosophy was dictated largely by the limited size of the PDP-8 computer; all programs are of minimal length, with optimization in that direction at sacrifice of speed, if necessary. As a result of this philosophy, for example, all of the arithmetic subroutines supplied with the computer were discarded, and replaced by somewhat slower, but more compact programs.

The system works from a predetermined list of stars, prepared in advance on paper tape and read once into core storage. The observation program then selects appropriate stars from this list, using the position and magnitude data included in the list. Upon selection of a target, the telescope is slewed to the calculated position of the star. At this point the star is usually in the field of the 10′ aperture and can be centered immediately. However, if there are uncorrected errors in position encoders or sidereal clock, or if the observation is being made at large air masses, the star may not appear in the aperture, necessitating an automatic search.

Once the star is found, it is centered in the aperture preparatory to the actual observations. These are made in two symmetrical sets, with the requisite air mass calculation made between sets on the basis of position encoder readings. Before final centering, a set of sky readings is taken north of the target. After viewing the star, the telescope is moved south, the second set of sky readings are made, and the data are reduced to visual magnitude and color indices for printout. Using magnitudes and color indices for zero air mass which have been stored with the star position data, the extinction coefficients for this point are then calculated. These are printed, and stored for later use, thus completing the observation.

The search routine, entered if the target is not in the aperture after a slew to its expected position, merely moves the telescope through a rectangular pattern about a center point, checking for the star at 5′ intervals (for the 10′ aperture). The rectangle size is adjustable, and has been set at 30′ by 30′ with good results.

The centering routine, used to bring the star close to the center of the viewing aperture, operates by moving the telescope across the star, noting the points at which the star first enters and then leaves the aperture, and interpolating between them to find the center point.

The computer can command the stepper motors to move one step (6 sec of arc) in any of the four standard directions. Slewing speed is then a function of the frequency at which these commands are issued, and so is controlled by the computer. In addition, the hour-angle drive can be turned on or off as desired. Slewing, then, consists of computing a desired position, and running a stepper motor in the right direction until the encoder position corresponds with this calculated position. However, the solution of the problems encountered in this inherently simple-minded process constituted the most difficult part of the programing effort.

Problems such as motor control and gear backlash were anticipated. Although the motors would run at 600 cps, they did not have enough power at that speed to overcome the starting inertia of the telescope. This required the program to start the motors at 200 cycles, increasing the speed gradually until the maximum running frequency is reached. The gear backlash, amounting to as much as 20 min of arc, is effectively eliminated by ensuring that all final motions are made going either north or west so as to use the same side of the gears consistently. Additional unanticipated difficulties were generated by the tendency of the motors to either stall out during the course of a slew, or to reverse their direction of motion on starting. Besides these problems, a defective Datex encoder on the declination axis gave incorrect readings when moving south. These problems led to a dynamic slewing routine. The procedure used recomputes motion requirements between each step of the motors but waits many steps before deciding that the resulting motion is incorrect. This works well, with the only drawback being an hour-angle speed limitation of 400 cps due to the time required for computations between steps.

Both the aperture size and the centering accuracy are adjustable. The 2′ or 10′ aperture may be selected by a sense switch. When the 2′ aperture is used, the search and centering routines are modified to take smaller steps.

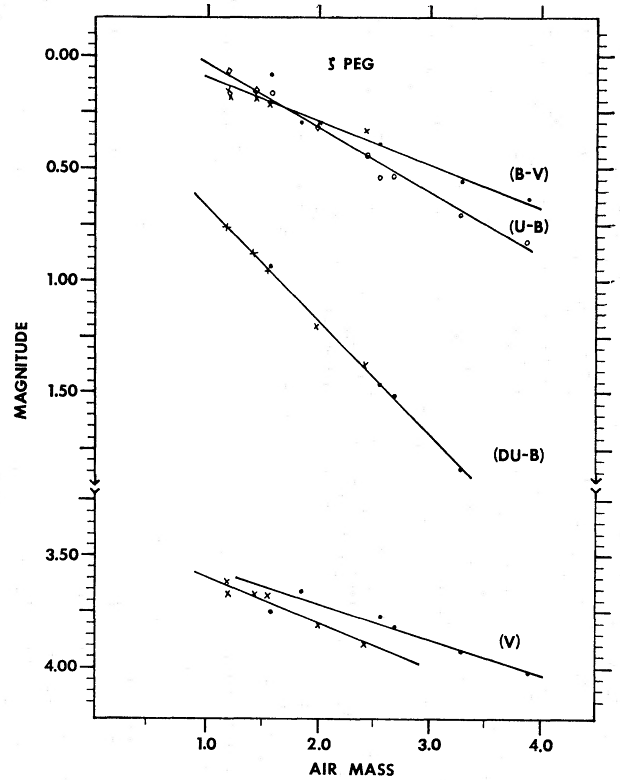

FIG. 4. Sample plot of extinction measurements obtained with the 8-in. automatic telescope on two different nights, for ζ Peg.

A symmetrical observation technique is used in order to eliminate any linear changes in equipment sensitivity, sky brightness, or atmosphere over the observing interval. The star is observed twice through each filter, with each data point the average of 262 000 readings over a 12-sec interval. The four observing filters are cycled in reverse order on the second observation set, for symmetry.

The data resulting from this observation sequence are reduced to visual magnitude m_v and color indices C_{b-v}, C_{u-b}, and C_{du-b}, which are used to calculate the desired extinction coefficients (cf. Hardie 1962). The individual measurements are also printed so that the data can be reduced by other techniques or utilized for the study of variable stars.

There are some additional features of the system which come under the miscellaneous category. The sidereal clock is also used to keep standard time, which is included with each set of data points and printed out with them. Three successive star-acquisition failures are used as a criterion for ascertaining cloudy conditions, in which case the system waits for 1 h before trying to observe again. Serious, uncorrectable failures are signalled by a computer-controlled alarm bell, and the system shuts down.

The system is programed to operate in the following fashion:

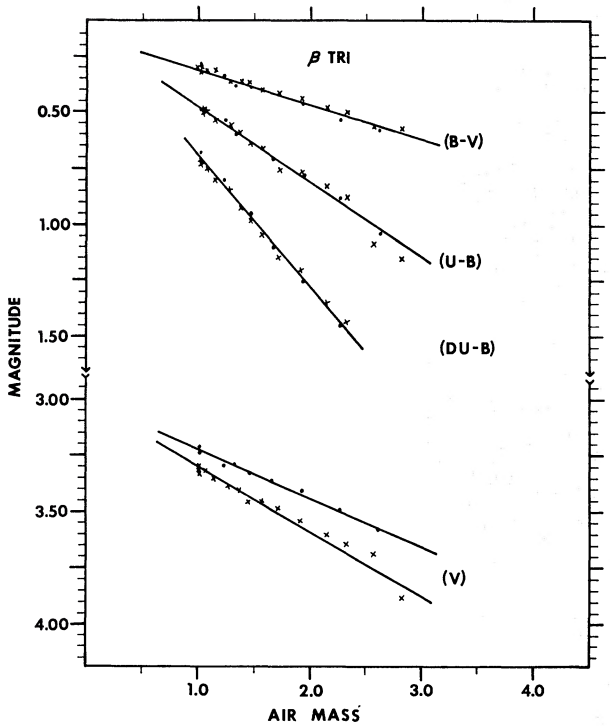

FIG. 5. Sample plot of extinction measurements obtained with the 8-in. automatic telescope on two different nights, for β Tri.

Upon being activated, the high voltage is applied to the phototube and the light level inside the shed is sampled. When sufficient darkness is found, the rain sensor is interrogated. If it is not raining, the roof is opened and the light level again tested. Observations as previously described may then begin.

Observing goes on until dawn is detected, whereupon the telescope is returned to its rest position and the roof shut. The system then waits until the next night to begin again.

Rain or clouds will shut the telescope down for 1 h before it begins again, while troubles such as power failure or malfunctioning roof cause a permanent halt.

V. OBSERVATIONAL RESULTS

A plot of the extinction measurements on two different nights is illustrated in Figs. 4 and 5. The resulting extinction coefficients are typical of those that have generally been found at Pine Bluff. For the visual extinction the values range from about 0.20 to 0.38 mag per air mass; $k(B-V)$ from 0.16 to 0.22 mag/a.m.; $k(U-B)$ from 0.30 to 0.40 mag/a.m. and for our interference filter short-wavelength ultraviolet system $k(DU-B)$ ranges from 0.45–0.60 mag/a.m. These results are in excellent agreement with results obtained by observers over the past few years using the Pine Bluff Observatory 36-in. reflector (Burkhead 1964). Not only are the variations from night to night found, but due to the larger number of observations possible with this system, variations in transparency over periods of an hour may be determined on many nights. The number of observations and their interval accuracy are illustrated in Fig. 6, which shows a portion of an extinction curve on an expanded scale.

Observers doing filter photometry on 36- and 16-in. telescopes at Pine Bluff can use the results obtained directly, while those doing photoelectric scanning can use the individual color measures to normalize a standard wavelength-dependent extinction curve.

A point of interest is the reproducibility of the zero air mass magnitude. On several good nights the total spread was on the order of five hundredths of a magnitude without attempting to correct for amplifier zero drift. This demonstrates the usefulness of a standard source used to remove instrument sensitivity. Since in this instrument we are using an uncooled multiplier (and observe variations of up to 20%) this is a virtual necessity.

It is clear that for the brighter stars systematic photometry could be carried out utilizing this instrument and might prove very valuable in establishing a set of standard stars and monitoring the light constancy of these stars. No such program has been instituted as yet. Some limited observations have been made, however, of possible δ Scuti variables. Light variations have been observed for two suspected δ Scuti variables (Mills 1967).

VI. CONCLUSIONS

This system has demonstrated that routine, remote observing can be done completely automatically. Extinction data can be collected and reduced even during

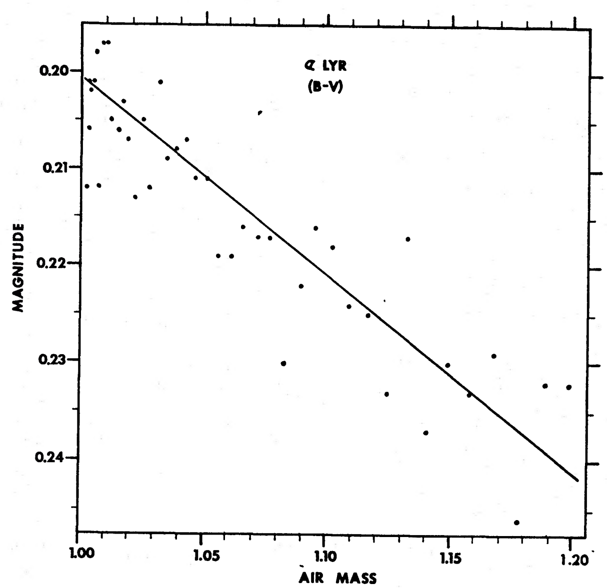

FIG. 6. An expanded scale of the extinction measurements in $B-V$ obtained during a portion of one night on the bright star α Lyr.

a Wisconsin winter, without interrupting the observing program of the astronomer. Such relatively inexpensive instruments could well be of value for other observatories in increasing the over-all efficiency of observing.

Probably the most instructive feature of this entire instrumentation development was the appreciation gained of the power of a programable digital system. Earlier we had constructed a servo-controlled extinction telescope utilizing special purpose circuitry and mechanical or wired-in logic operations. Any changes in the mode of operation or improvement in performance required rewiring or machine shop work. Problems involving backlash, hunting, and setting accuracy could only be solved by replacing bearings or gears. In contrast, mechanical difficulties were solved and operational changes effected by reprograming the computer controlled system.

A result of this effort is the proof of feasibility and utility of a more completely automated observatory. This system could be considered an input–output device for a somewhat larger computer that could control the larger telescopes, as well as data collection devices such as photometers and spectrum scanners. An astronomer would be needed because the observing would not necessarily be routine, but he could be inside using the full capabilities of the observatory rather than warming up between data collection cycles. The primary observatory computer could be tied to a more powerful central computer complex for further extension of its capabilities.

Another important consideration is the fact that the computer capabilities are available for use with all auxiliary instrumentation designed for use on the main telescope. Currently we operate a rapid scanning spectrometer under computer control and storage. We plan to use a data-phone line to provide additional spectrometer flexibility by use of a larger computer.

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