No. 16. AN INFRARED STELLAR SPECTROMETER

by G. P. Kuiper, R. Goranson, A. Binder, and H. L. Johnson

November 6, 1962

1. *Introduction*

In 1946 Kuiper initiated a program of spectral observation of the brighter planets and stars in the region 1.0-2.5μ with a prism spectrometer, using a Cashman lead-sulfide cell as detector. The resolution, $\lambda / \Delta\lambda$, was quite low, about 80, but could be increased to about 250 on the brightest stars and the planet Venus by the use of an analyzing slit in front of the cell. In laboratory studies using brighter sources, the resolution could be increased to 1000-2000. In spite of the limited resolution, several results of interest were obtained (Kuiper, Wilson, and Cashman, 1947; Kuiper, 1947, 1952, 1957; I.A.U., 1950).

More resolution was clearly needed and was attainable by the use of gratings (cf. p. 11 of these *Communications*). Through good fortune, an experimental grating spectrometer of the Ebert type, built by Mr. Leon Salanave for a meteorological project, was made available to the Laboratory by Dr. A. R. Kassander, Director of the Institute for Atmospheric Physics. The instrument was adapted by Kuiper and Salanave for attachment to the 82-inch McDonald telescope in January 1961 and used during a short observing session in February 1961. The experience gained during this and two subsequent observing runs, in April and June 1961, led to further improvements and detailed design specifications for a more definitive instrument.

A new spectrometer was built according to these specifications in the Laboratory shop during the summer and fall of 1961. The two spherical mirrors of the Salanave spectrometer were used again, and also the rotating sector, the finding devices, and the electronic system used in Kuiper's earlier prism spectrometer. The new spectrometer was used in three subsequent observing sessions with the 82-inch telescope (December 1961, March and August 1962) and in several brief runs with the 36-inch telescope of the Kitt Peak National Observatory. While further attachments are planned that will increase its power by another factor of 10, the instrument is now described since the basic design is not expected to be altered and because new scientific data have been obtained with it. A sample of such data was reproduced in these *Communications,* pp. 11-19. The electronic system was designed by Dr. H. L. Johnson in 1956 and built by Mr. A. Gardiner that same year. The system was used with Kuiper's prism spectrometer and is used here without change.

The problem of the relative efficiency of a one-channel grating spectrometer and a Michelson-type interferometer has recently been raised at several scientific meetings. A discussion of this problem is found in *Communications No. 15,* Section 5.

2. *Design and Description of the Spectrometer*

The spectrometer uses photoconductive detectors, PbS in particular, cooled to dry-ice temperature. These detectors are available in various sizes, down to 0.1 mm in width. If the detectors are used directly in the focal plane of the camera, the spectral resolution is determined by (1) the angular dispersion of the grating, (2) the focal length of the camera (f), and (3) the detector size. For a grating with 600 lines per mm used in the first order, the linear dispersion is of the order of 1A = 0.00006 f. If $f =$ 60 cm, 1A in the spectrum measures 0.036 mm, or 1 mm = 28A. For a detector width of 0.25 mm, the resolution will be about 7A; for 0.1 mm, about 3A. Since in the spectrometer the collimator and camera have equal focal length, and since the stellar image is rarely less than 0.1 mm in diameter ($0\overset{''}{.}74$ for the

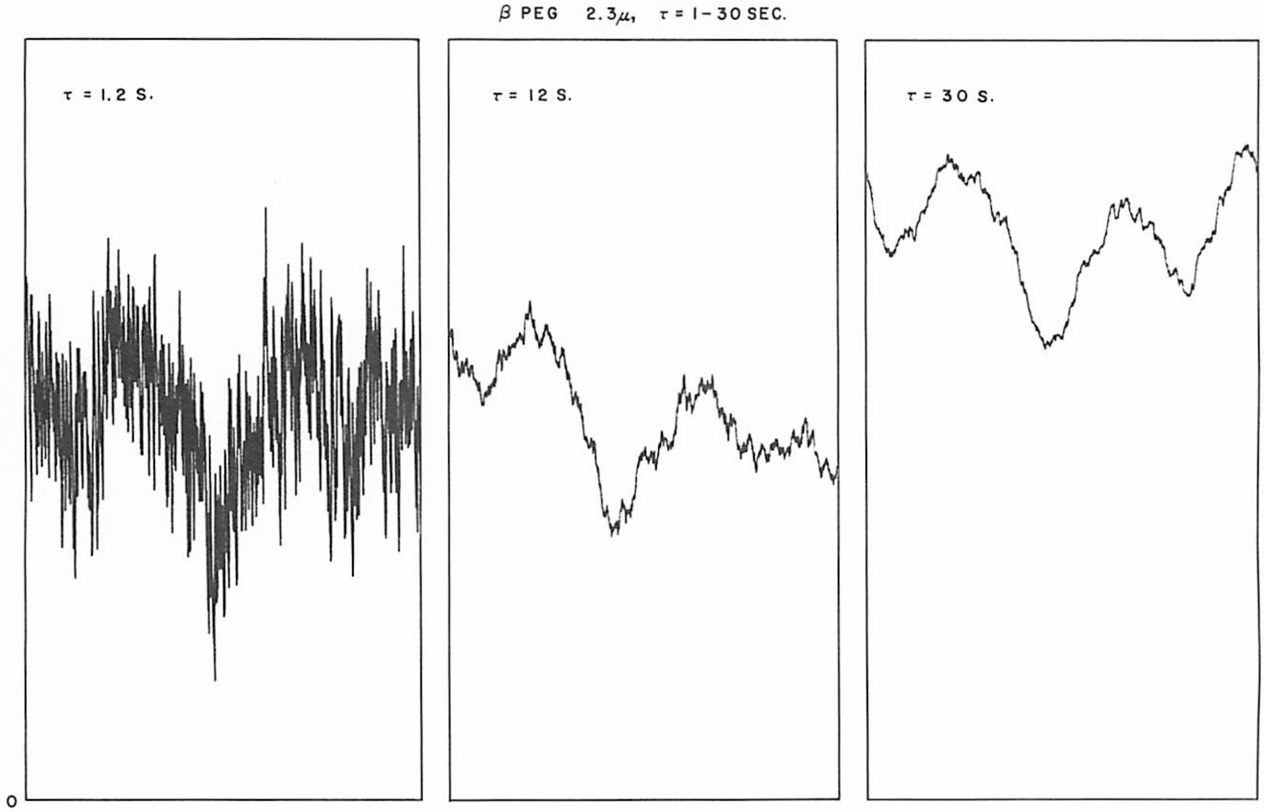

Fig. 1. CO band at 2.3μ in β Pegasi, recorded with $\tau = 1.2$, 12 and 30 seconds.

82-inch telescope), the lower limit of the detector size, 0.1 mm, is a practical one. At 15,000A, resolutions up to 5000 are therefore possible if the image size is well below 0″.7, or, with images of 0.1 mm, resolutions up to 3500. Somewhat increased resolution would be practicable by increasing the focal length of the spectrometer camera.

A series of interchangeable Bausch and Lomb gratings was acquired, blazed respectively at 1.0, 1.6, 2.0, 3.0, and 4.0μ. The first two have 600 lines/mm; the next two, 300 lines/mm; and last, 150 lines/mm. The 1.6μ grating has been used up to 2.5μ, giving dispersions about 2½ times that of the 2μ grating in the 2-2½ μ region, at considerably reduced intensity, however.

A series of sizes of cells was decided upon to obtain maximum versatility in spectral resolution and speed, starting with the minimal dimension of 0.1 mm. The dimensions are 0.1, 0.25, 0.5, 1.0, and 2.0 mm in width, and the constant length of 2.0 mm was selected in view of the expected maximum image sizes and image excursions under average operation conditions. For a camera focal length of 60 cm and a grating with 600 lines/mm, the cells listed give at 1.6μ the resolutions 5000, 2000, 1000, 500, and 250. The use of wider cells at lower resolutions will, of course, be advantageous only if the sensitivity is thereby increased. Theoretically, this should be the case, but only with the square root of the width. This is so because for a constant length the cell noise increases as the square root of the cell width.

Cells of the desired dimensions were procured from two companies, Eastman Kodak (Ektron) and Infrared Industries, and were found to have similar sensitivities. About five cells of each dimension were intercompared at dry-ice temperature and the best two selected in each case. Since the spread in sensitivities for a given dimension was found to be about a factor of 10, this pre-selection was essential. Recently, custom-made cells of exceptional sensitivity have become available, and an addition to be made to the spectrometer will incorporate such a cell.

The best two of the 0.1 mm cells were found to be quite sensitive, so that one of them has been used in most observations to date.* The earlier records

---

* Both cells have since lost all sensitivity.

were made with a sensitive 0.25 mm cell. The signal-to-noise ratio may be increased by lengthening the observations, as the square root of the interval. This is done by the use of various time constants, $\tau = 1.2$, 12, and 30 seconds. An increase in precision of a factor of 5 is expected by switching from the smallest value of τ to the largest, and by scanning the spectrum more slowly in the same ratio. The empirical effects are illustrated in Figure 1, which shows traces of the 2.3μ band of CO in β Pegasi. At a given scanning speed, the use of a longer τ corresponds, of course, to a proportionally decreased spectral resolution. If the scanning speed is appropriately reduced, the spectral resolution may be regained.

The stellar signal is chopped at 60 cps by means of a two-blade sector placed on the shaft of an 1800 rpm synchronous motor. This frequency is known to be close to optimum for PbS detectors used at dry-ice temperature. The cell voltage used is adjustable from 30-90 V. The amplifying system is described in Section 3.

The optical train and the housing of the spectrometer are shown diagrammatically in Figure 2. The camera and collimator mirrors are spherical, about $f/8$, of 7.5 cm diameter and 59 cm focal length. At the Cassegrain focus of the 82-inch telescope the beam is $f/13.6$, and at the 36-inch Kitt Peak telescope the f ratio is about the same. Therefore, the dimensions of the mirrors are ample for these telescopes. In the usual Ebert arrangement, the axis of the grating table is normal to that shown in Figure 2. The design used here was found preferable because it allowed the guiding microscope and the wide-angle scouting eyepiece to be mounted on opposite sides of the spectrometer frame, both close to the slit, free from the bulk of the cooling chamber. The resulting optical aberrations were found to be negligible for the sizes of the detectors in use, both by visual inspection and by computation.

The spectrometer has gained materially from the introduction of a diagonal flat in the camera beam. First, it allowed a ready interchange of cells, as may

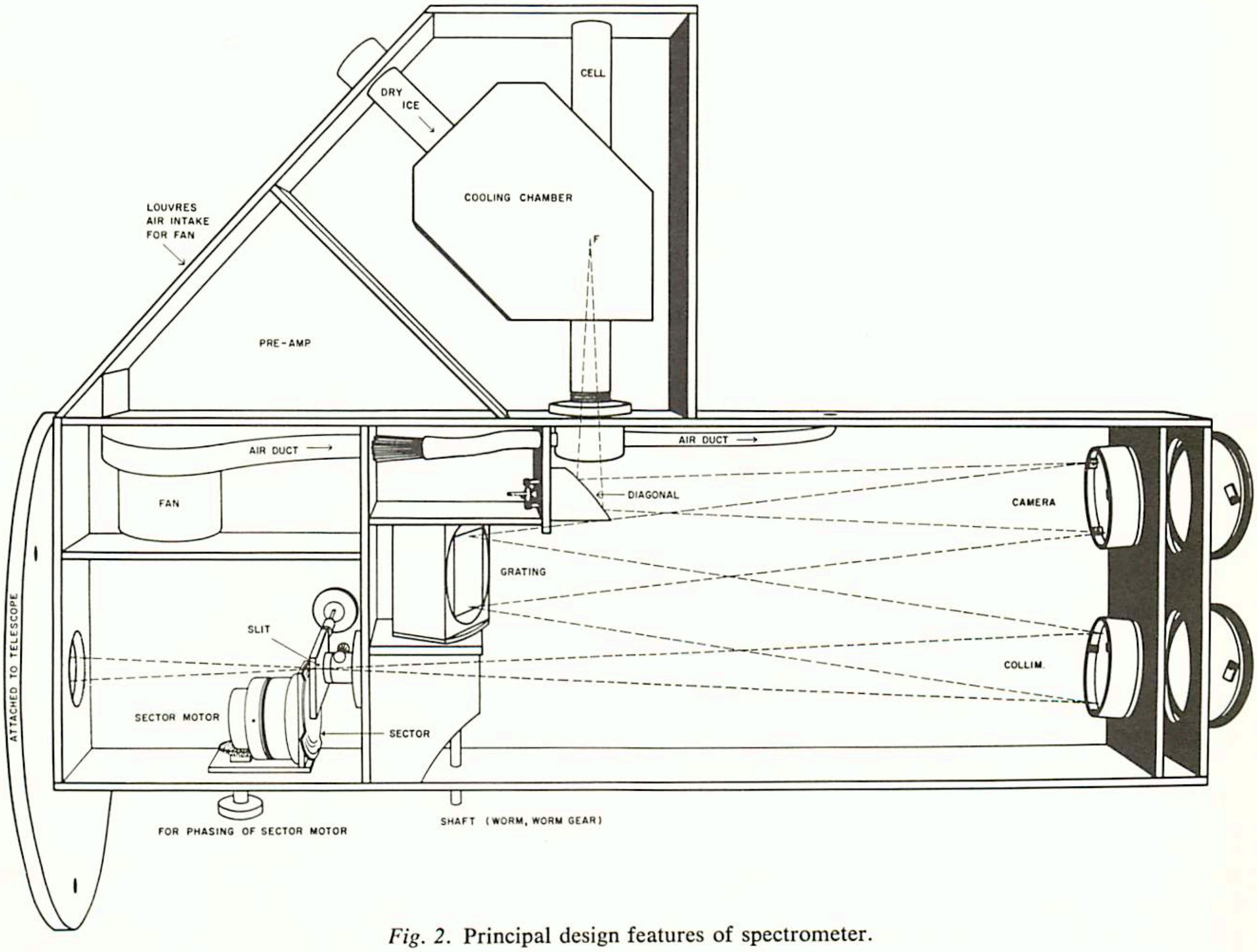

Fig. 2. Principal design features of spectrometer.

be seen from Figures 2 and 3. Second, it permitted the cold chamber to be made substantially larger and the insulating mantle to be increased in thickness, thus insuring better temperature control of the cells, and allowed the installation of a filling tube at an angle practical both at the telescope and in the laboratory. It also insures that the dry ice and acetone be concentrated around the cell, even for a partial filling, and prevents leakage of acetone during normal operations.

The use of gratings requires the separation of orders by means of filters. Each filter is mounted in a filter holder that is screwed into the base of the cell housing tube, as shown in Figure 3. The filter serves at the same time as a seal of this tube, preventing moisture from condensing onto the cooled cell. The filter itself is prevented from being fogged by an airflow conducted around the filter by means of a manifold. The airflow serves the further purpose of cooling the preamplifier section. Various design features of the spectrometer box were tested before construction began on a plywood model.

Three filters have been in use: a red filter (RG 8) for the 1μ grating; a 1μ filter (Corning 2540) in use for the 1-2μ region with the 1.6μ grating; and a 2μ interference filter for use beyond 2μ. The latter filter has no transmission below 1.9μ and transmits 85% between 2.0 and 2.5μ.

The collimator and camera mirrors are adjustable by push-pull screws, which are protected by a second outer wall that contains access doors. The alignment of the optics has proved very stable, in spite of the transportation between the Laboratory and the observatories. The only necessary adjustments are those resulting from changes of gratings or cells. They are made by minor corrections to the camera tilt.

The grating table has been made very rigid because wavelength measurements require high precision in the grating control. The rigidity has been achieved by supporting the shaft of the grating box in bearings that are placed in well-supported partitions in the spectrometer. The lower section of the grating shaft was split to allow the passage of the radiation coming from the slit. The gratings are mounted in identical cells placed in the rotatable grating box. The adjustments provided for the grating cells resemble those of the camera and collimator mirrors.

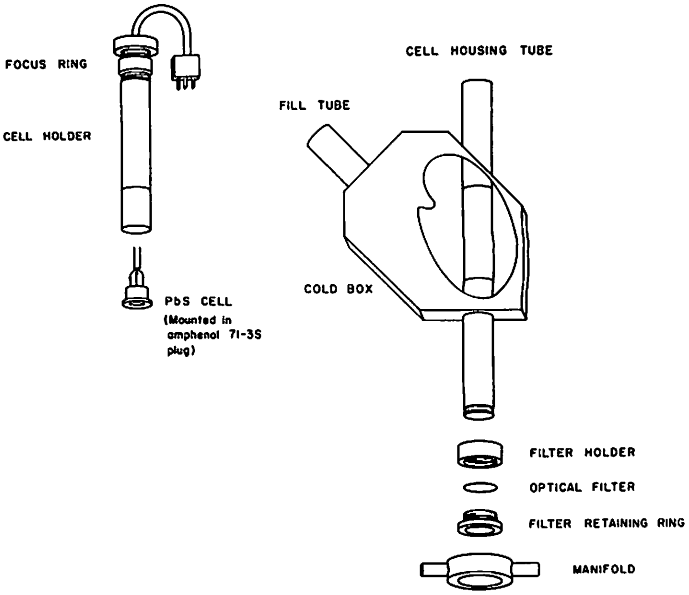

Fig. 3. Components of spectrometer.

The grating box is driven by a precision worm and worm gear. The worm gear has a comparatively large diameter for added precision and has 180 teeth. The worm is turned by a synchronous motor with built-in gear reductions. Six reductions are provided which give the following scanning rates on the 1.6μ grating: 0.2μ (2000A) in 2.5, 5, 12.5, 25, 50, and 125 minutes. For the 2μ grating the dispersion is less by a factor of about 2.5, and the scanning rates are correspondingly faster. The scan angle of a grating may be read to about 0°.1 by means of a divided circle and indicator, which can be illuminated when read. A table put on the spectrometer provides conversion of circle reading to wavelength for each of the gratings.

The mounting of the cells is shown diagrammatically in Figure 3. The cell is surrounded by a brass section, shown about ¼ inch high in Figure 3, which provides good thermal conductivity. The upper section of the cell holder is nylon, a good insulator. As shown in Figure 3, the cell holder is placed in the housing tube which consists of three sections. The central section is brass, which provides good contact with the coolant outside; the end sections are Monel, a low-conductivity metal, to reduce heat exchange with the surroundings, including the filter holder. The cell is kept in the correct focus by means of the focusing ring which serves as a stop. The desired position of the ring is found from a dummy focusing tube of identical dimension which allows the observer to see the spectrum. The use of the zero-order image of the slit, illuminated by an artificial source, has been found practical and adequate. The orientation of the cell and its holder is fixed by means of a positioning pin. The focusing tube also is used to check on the grating alignment when gratings are changed. If the grooves are not precisely parallel to the scanning axis, the spectrum will sweep at a small angle and slowly move off the cell. The higher orders of the visual spectrum indicate the position of the infrared.

Guiding is provided in the customary manner by means of a microscope that views a slit which is inclined 5°. Slit widths up to 2.5 or 3.0 mm may be used. The slit area visible is a circle of about 10 mm diameter. The length of the slit used may be limited by a V-shaped bar. However, since the cells are only 2 mm long, the effective slit length on a disk (moon or large planet) is 2 mm.

Stars are observed by using the spectrometer in slitless form. The slit is normally opened 2½ to 3 mm and left full length. Guiding is accomplished by means of the image reflected from a thin quartz plate moved at will just in front of the slit. A reticule in the microscope eyepiece provides reference marks for accurate guiding. For faint red stars (such as o Ceti at minimum) the field of the slit is so dark that the reticule cannot be seen. A dim field illumination of adjustable intensity is provided to remedy this situation. For the grating spectra, the contribution to the spectral energy by the field light is entirely negligible.

Since the lines of the grating are always parallel to the slit, the dispersion is perpendicular to the slit. If the slit is placed east-west, as is customary, slight errors in guiding in R.A. will have no effect (at least if the cell has uniform sensitivity along its length). Displacements in declination, however, will result in spurious wavelength shifts, and should be avoided. For stars this poses no problem as long as the telescope guides well. For a disk there is no problem either as long as the illumination is uniform within the slit width. For moving objects, such as the Jupiter satellites, the guiding in declination must be done with care to avoid wavelength errors. Variable atmospheric dispersion through its declination component can cause small changes in the dispersion on the spectral records.

The assumption that the cells are uniform in sensitivity along their length is not strictly true. By drifting a star slowly in R.A., along the slit, at a constant position of the spectral scan, the sensitivity profile of the cell for a given wavelength may be determined. Figure 4 shows the profiles so obtained for the two sensitive cells of 0.1 mm width. The different recordings are not entirely identical because of small irregular motions of the drifting star, due to seeing effects. On the basis of these tests, cell "Z" was accepted as the more desirable, with the guiding done to make the energy fall on the flat high portion of the curve.

A scouting eyepiece of lower power (800 x on the 82-inch) and wider field can be inserted above the slit and guiding microscope. This device serves a second purpose. The eyepiece can be removed and the tube holding the diagonal prism rotated 180°, thus pointing toward the slit rather than toward the sky. Then an artificial light source can be mounted in place of the eyepiece and used for test purposes, focusing, etc.

The ideal scanning procedure for stars of different magnitudes would be to increase both the scanning rate and the time constant for the fainter stars, and to decrease the chart speed of the recorder correspondingly, so that all spectral records would show the same resolution. In practice this can be done over a limited brightness range only, since the spectral scans would become impossibly long for faint stars. Within this range, however, the ideal scanning procedure can be approximated with the present instrument. The time constants provided range over a factor of 25, the scanning rates over a factor of 50, and different chart speeds are available. During the actual observations, three scanning rates have been used in nearly all cases: a fast rate for purposes of orientation (such as the determination of the optimum gain setting), and the 50- and 125-minute scans (cf. above) for the actual records. The 50-minute scan is normally combined with a chart speed of 2 minutes per inch, and the 125-minute scan with a chart speed of 5 minutes per inch. Records obtained with these two combinations have the same dispersion. They will have the same resolution as well if the time constants used are also in the ratio 1:2.5 and the electronic noise is either negligible or similar (which requires that the stellar magnitudes differ by 0.5 mag.).

Ideally at least 3 τ should be used per resolution interval, which would insure that the amplitudes of just-resolved absorptions be represented to a precision of e^{-3} or 5%. In practice, 2 τ was often used as a good compromise between the reduction of noise and the resolution of detail.

Distinctly lower resolutions and greater speeds are obtained by use of a 30° Littrow quartz prism with a silvered back. This prism is mounted in a holder similar to those used for gratings, and is thus interchangeable with them. Spectral scanning proceeds in the same manner as for the gratings, and

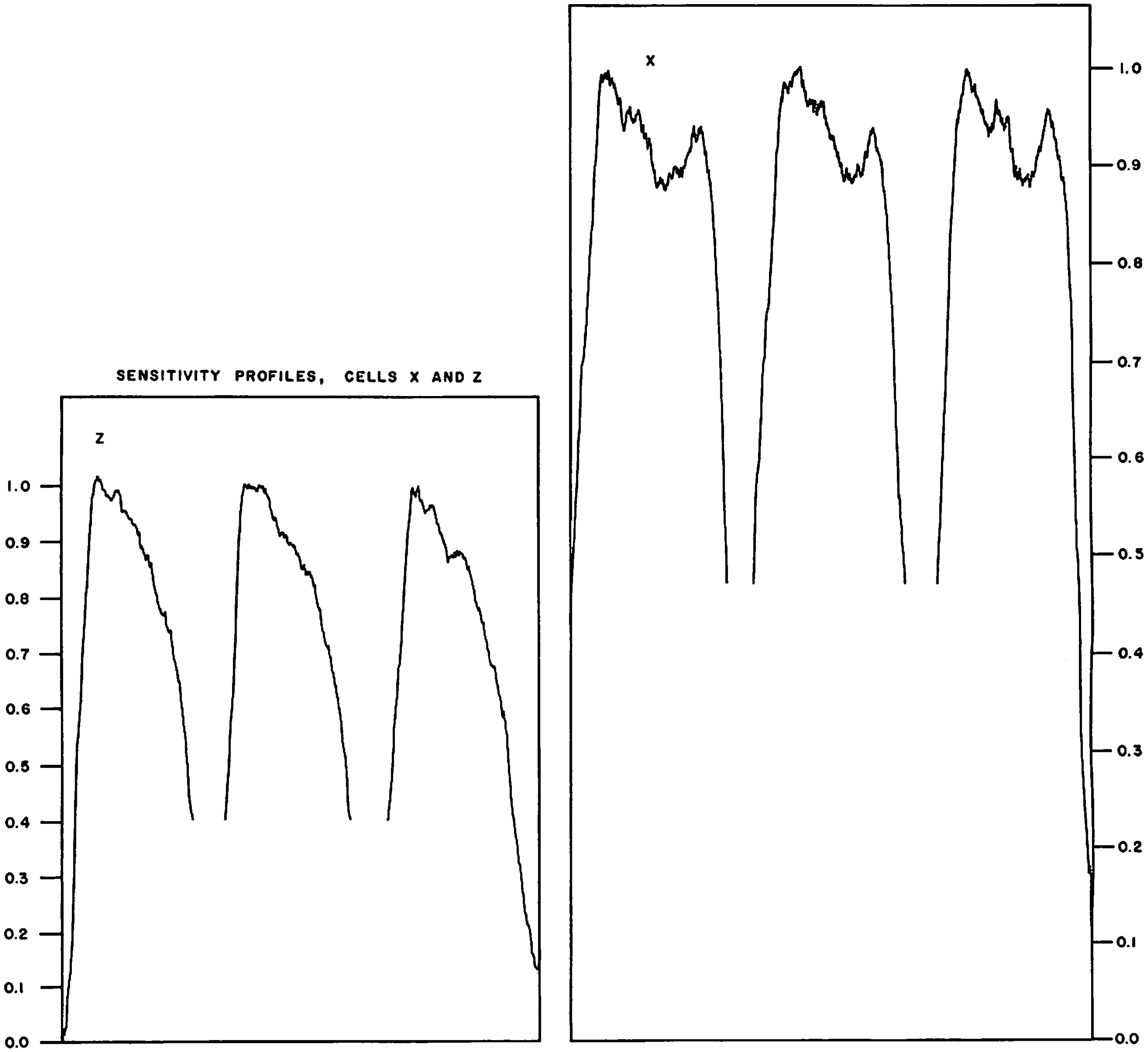

Fig. 4. Sensitivity profiles of 0.1 mm PbS cells along their 2.0 mm lengths.

the dispersions and resolutions are about 20 times smaller than for the 600 lines/mm gratings. This lower dispersion is suitable for the determination of the energy distribution in stars, planets, and satellites between 0.5-2.5μ.

The following additional interchangeable detectors are being installed: (1) an Infrared Industries PbS detector of very high sensitivity, ¼ x ¼ mm in size, used with a short-focus Fabry lens imaging the telescope mirror onto the detector, and equipped with a set of analyzing slits to obtain resolutions ranging from 200 to 4000 at 1.6μ; and (2) a ten-channel PbS detector, briefly described on p. 19 of these *Communications.* A separate spectrometer for the 3-5μ region, using an InSb cell, is under construction. It will use the 3.0μ and 4.0μ gratings and a LiF Littrow prism of 30° apex angle.

The spectrometer and amplifier attached to the 82-inch telescope are shown in Figure 5.

3. *The Amplifier*

The amplifier and preamplifier system, illustrated in Figure 6, was designed and built by A. J. Gardiner and H. L. Johnson. This system consists of a preamplifier having a voltage gain of 10, followed by an AC amplifier having a maximum voltage gain of 200. This AC amplifier is tuned, by the twin-T filter in the feed-back loop, to 60 cps, the frequency at

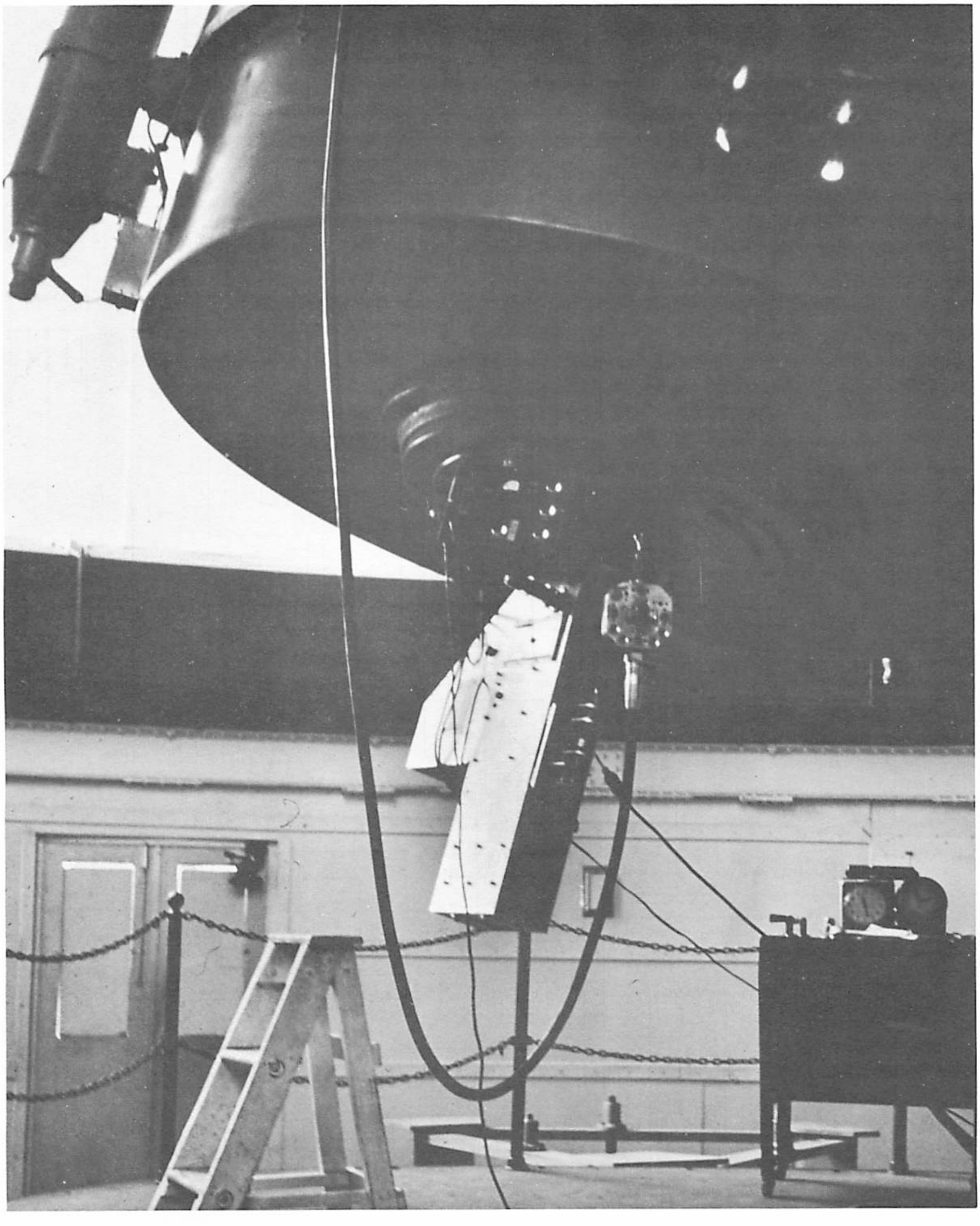

Fig. 5. Spectrometer on 82-inch telescope.

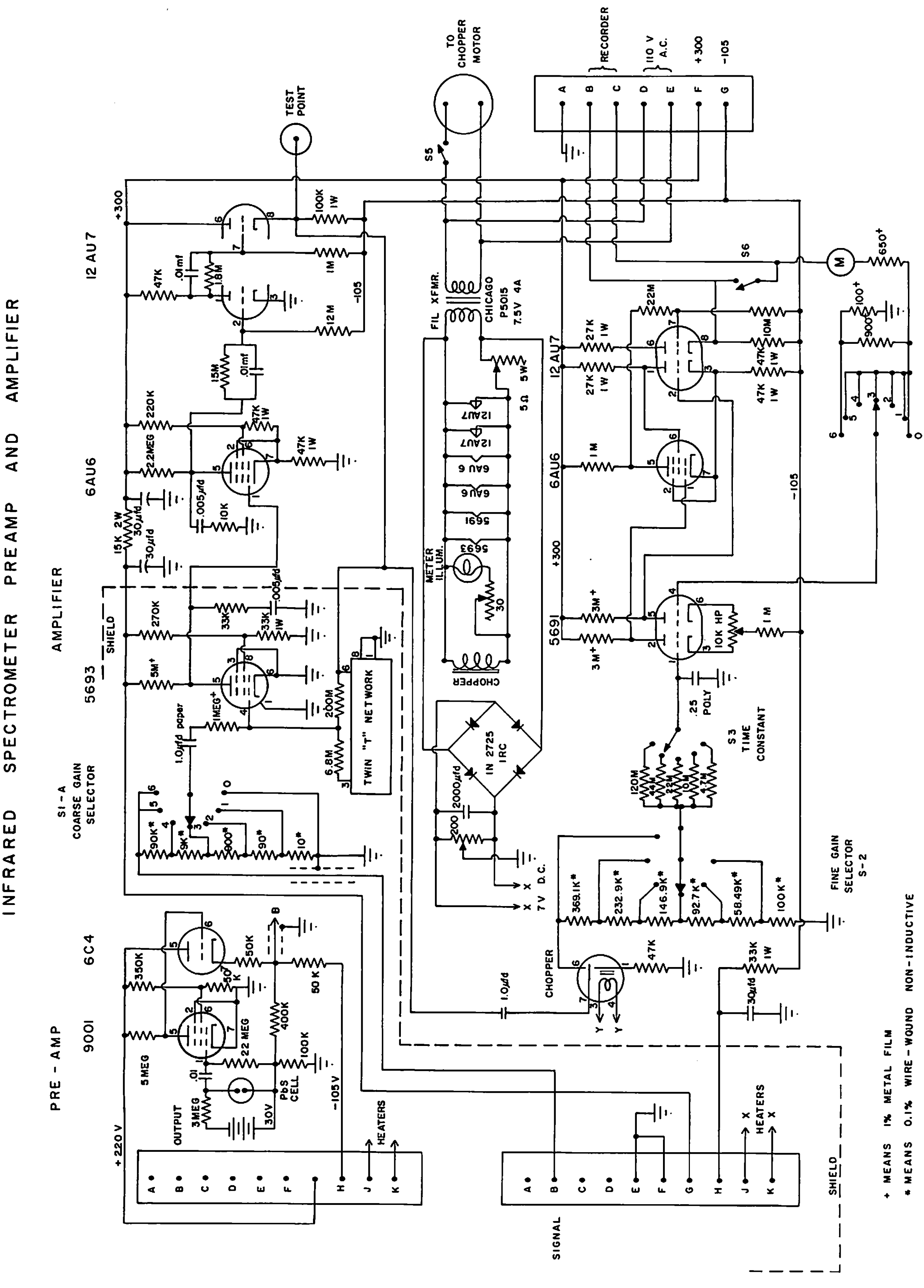

Fig. 6. Design and wiring diagram of preamplifier and amplifier.

which the incoming radiation is chopped. The bandwidth of the AC amplifier is approximately 5 cycles per second.

The output of the AC amplifier is fed to a mechanical chopper acting as the synchronous rectifier; the DC output of the rectifier is fed to the DC amplifier and then to the strip-chart recording meter. The overall gain of the amplifier may be changed by several factors of 10 with the switch attenuator at the input of the main AC amplifier, and in ½ mag. steps by the attenuator at the input of the DC amplifier. The total range in gain is 10^6 or 15 mag., in steps of ½ mag.

The overall bandwidth of the amplifier is set by the RC time-constant at the input of the DC amplifier; these time-constants range from 1.2 seconds (bandwidth, 0.13 cps) to 30 seconds (bandwidth, 0.005 cps).

The regulated power supply is conventional, supplying +300 volts and −105 volts, and is not illustrated.

REFERENCES

International Astronomical Union 1950, *Trans. I.A.U.*, Vol. 7, Frontispiece and pp. 371, 436-440.

Kuiper, G. P. 1947, *Ap. J.*, *106*, 251-254.

———. 1948, *The Atmospheres of the Earth and Planets*, ed. G. P. Kuiper (Chicago: University of Chicago Press), chap. 12.

———. 1952, *ibid.*, 2d ed.

———. 1957, *A. J.*, *62*, 245.

Kuiper, G. P., Wilson, W., and Cashman, R. J. 1947, *Ap. J.*, *106*, 243-250.

TABLE OF CONTENTS