# NO. 22. THE WAVELENGTH DEPENDENCE OF POLARIZATION*

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Preliminary results are described of a program of polarimetry and photometry. Astronomical telescopes and a differential polarimeter are used with calibration by a Lyot depolarizer. The wide-band filters have effective wavelengths between 3250 Å and 9900 Å. The problems of instrumental polarization and depolarization are discussed; most of the instrumental effects can be avoided by proper aluminization of the telescope mirrors. The multiple molecular scattering of the sunlit sky and of the poles of Jupiter is closely represented by the Rayleigh-Chandrasekhar theory; the optical depth at the Jovian poles is 0.4–0.8. The same particle sizes that explain the interstellar reddening, 0.05–0.3 $\mu$, are found from the interstellar polarization. Strong polarization-wavelength dependence is found for Venus and for lunar regions, but the detailed explanations require extension of the wavelength range. The range of wavelengths will be extended by using high-altitude balloons and spacecraft.

## *I. Introduction*

The primary purpose of this study is to compare the particles that are between the planets with those between the stars. The sizes of these particles probably are near the wavelength of light, and the polarization of the light scattered by such particles is strongly wavelength-dependent (see ref. 1, pp. 152–153). Polarimetry over a wide range of wavelengths may therefore yield many parameters from which to study the particle size and refractive index. Colors are also determined, in addition to the amount and the orientation of plane-polarization. No measurements have as yet been made to distinguish elliptical polarization.

Strong wavelength dependence of the polarization was discovered on Venus and other astronomical objects. Apparently only little is known to date about the dispersion of polarization; the available references are given in the last paragraph of Section III. The present paper contains a summary of our results (the details are being published[2–5]), and of preparations for future work in order to extend the range of wavelengths.

## *II. Instrumentation*

Techniques of polarization measurements have been discussed in a chapter by Hiltner,[6] who built and tested a two-beam polarimeter in 1951. Our photometer/polarimeter was assembled in 1958, and the equipment and reduction method have been described in detail.[7] A Wollaston-type prism, with two photomultipliers following it, is successively set at six or seven position angles. At each angle a pair of integrations is made with and without a Lyot depolarizer inserted in the incoming beam; thus a nearly simultaneous calibration is obtained. Lyot depolarizers have been described[8–10]; they consist of two quartz disks, with thicknesses $e$ and $2e$, cut parallel to the optical axis; the two disks are put together with 45° between the axes.

Because of close calibration and simultaneous observation of both polarization planes, the measurements are not affected by flexure of the telescope and polarimeter, or by thin clouds and poor seeing (provided the seeing disk is smaller than the photometer diaphragm). When the objects are bright enough so that there are no statistical problems with dark current, the precision of the published results is with probable error $\pm 0.07\%$, or $\pm 0.0015$ mag. (The percentage polarization being defined by $P = 100\,(I_1 - I_2)/(I_1 + I_2)$, or in astronomical magnitudes $p = 2.5 \log_{10}(I_1/I_2) \simeq P/46.05$; $I_1$ and $I_2$ are the intensities of electric-vector maximum and minimum, respectively.) A paper has been published[3] giving the details of the determination of the precision. The precision in a program on Venus is $\pm 0.055\%$.

The reductions for each position angle, $\mu$, of the Wollaston prism are made with a simple least-squares solution of

$$\cos 2\mu\,(a \cos 2b) + \sin 2\mu\,(a \sin 2b) = f(m),$$

where $f(m)$ is a function of the tube outputs, $a$ is the amount of plane polarization, and $b$ is the position angle

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of the electric-vector maximum. A method of calibration of the position angle has been described.[7]

Four different telescopes have been used to date: the 82-in. (208-cm) and 36-in. (91-cm) Cassegrain telescopes of the McDonald Observatory, the 36-in. (91-cm) prime-focus reflector of the Goethe Link Observatory, and the 36-in. (91-cm) Cassegrain telescope of the Kitt Peak National Observatory.* A Barlow lens was used at the Goethe Link telescope, so that all observations were made at an $f$-ratio near $f/13$, with focal plane diaphragms of 4 to 30 sec of arc in diameter. The filters are combinations of standard Corning and Jena filter glasses with widths between 300 and 1400 Å (in exceptional cases as wide as 2700 Å). With the ultraviolet filters, solutions of nickel-sulfate and copper-sulfate are used to eliminate red leaks.[7] The present range of wavelengths is $1/\lambda = 1.01$–$3.08\ \mu^{-1}$ (9900–3250 Å). We use $1/\lambda$ in all wavelength designations, rather than $\lambda$, for it is the number of waves across the particle that characterizes the scattering properties.

After the description of the photometer was published[7] the following improvements were made to the equipment. In addition to RCA 7265 photomultiplier tubes for the ultraviolet, and RCA 7102 for the infrared, we now also use EMI 6255S tubes. The EMI tube has a fused silica window, and the nickel-sulfate filter was slightly modified (stock thickness Corning 9863 plus 8.7 mm thickness of a solution: 412 g $NiSO_4 \cdot 6H_2O$ plus 5.2 g $CuSO_4 \cdot 5H_2O$ plus 1 liter $H_2O$; and a disk of 1.6 mm thickness of fused silica). Spectrophotometer tracings have been made for our liquid filters at temperatures between 0°C and 45°C, and no shift in the effective wavelengths was found greater than about 20 Å. However, if one should use such liquids to determine precisely the filter characteristics, especially at the short-wavelength side, rather than in the present application to eliminate red leaks, one must indeed guard against temperature variations as they affect the filter width and over-all transmission. We are indebted to J. S. Neff for pointing out these effects, and to S. F. Pellicori for making the spectrophotometer tracings.

### *III. Checks of Reliability*

The reliability of the polarimetric results is determined from laboratory checks, and from an intercomparison of the obtained results. Nonpolarized stars are observed during each observing session. These are near-by stars, and it is usually known from previous observations that they show very little polarization, if any. About ten stars per observing run are observed, chosen at various galactic longitudes so that their planes of polarization, if any, should be oriented approximately at random. The average of the observations on these ten stars is taken and, because of the supposedly random orientations, the average should be near zero.

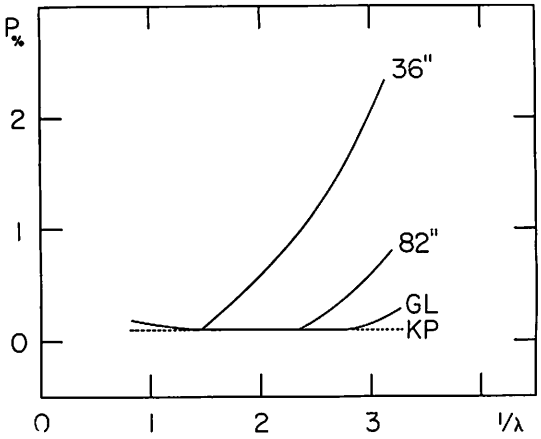

Fig. 1. Ordinates: percentage polarization. Abscissae: reciprocal of the wavelength in microns. Polarization introduced by the aluminized mirrors of the McDonald 36-in. (91-cm) and 82-in. (208-cm) telescopes (in 1959), the Goethe Link 36-in. (91-cm) primary mirror (1960), and the Kitt Peak 36-in. (91-cm) reflector (1961).

The findings on the instrumental polarizations caused by aluminized mirrors were published[2]; some mirrors have appreciable polarization, especially in the ultraviolet, as is shown in Fig. 1. The explanation is sought either in a diffraction effect, or in a differential absorption, in the crystalline structure of the aluminized layer. The effects are probably caused by asymmetric procedures during aluminization. The effects apparently can be avoided by using the glow discharge sparingly, preferably from electrode disks that are parallel to and slightly larger than the mirror surface. In Fig. 1, a residual polarization of 0.11% ± 0.03 appears common to all four telescopes with different position angles at different wavelengths. The residual polarizations, if real, apparently originate within the photometer.

At least as important as the tests for instrumental polarization are those for instrumental *de*polarization. We usually order two identical Wollaston prisms whenever one is needed. One of the two is, of course, installed in the polarimeter. During the test the second Wollaston is mounted in front of the telescope, or immediately in front of the polarimeter, and the light of one of its beams is observed. Should we be able to isolate one of the beams perfectly, the observed amount of polarization is 100%, provided, of course, that the mirrors, the Wollastons, and the polarimeter are perfect. It has been found before[2] that the aluminized mirrors of the McDonald 208-cm telescope were free of depolarization effects; the same conclusion is presently derived from a series of tests on the 91-cm mirror of the

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* Recently, the 21-in. (53-cm) reflector of the Lowell Observatory has been used.

Goethe Link Observatory. Slight depolarization was found in the Wollaston photometer,[2] but some of this defect may not be real. Most of the instrumental depolarization previously reported[2] must be ascribed to multiple scattering by the air in front of the photometer, rather than to multiple scattering within the Wollaston prism. We have now succeeded in eliminating most, if not all, of such scattered light during the tests; we are indebted to R. E. Samuelson for his help. With various filters, 27 observations were made; the average of the observed polarization is 97.90% ±0.24 p.e. No wavelength dependence was found; all of the usual filters were employed except the one in the extreme ultraviolet, at $1/\lambda = 3.08$, for lack of a suitable light source. The deficiency of the depolarizer[2] is 1.20%. It follows that one Wollaston prism causes 0.45% depolarization. The photometer, that is one Wollaston plus depolarizer, then has 1.65% deficiency. For ease of conversion, a *correction factor* is defined, by which all observed amounts of polarization are multiplied before publication. The presently determined correction factor is $100/(100 - 1.65) = 1.0168$. The polarization is now known in *absolute* amount; except for objects that are as strongly polarized as the sunlit blue sky, the accuracy is better than ±0.1% (±0.002 mag.).

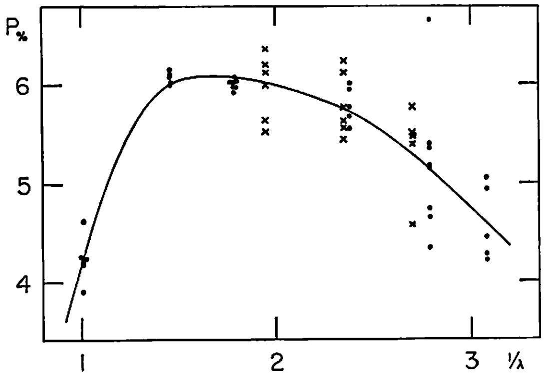

Fig. 2. Interstellar polarization, observed by Behr (crosses), and in the present program (filled circles). The apparent small scatter at $1/\lambda = 1.46$ and 1.79 is a result of the normalization process.

Intercomparison of our observations indicates that the polarimeter gives consistent results. For instance, large amounts of polarization have been found for lunar regions near quarter phase, as shown below in Fig. 8. Toward zero phase, however, these polarizations uniformly vanish, as is expected from symmetry considerations. The position angles of polarization maximum were found on the sunlit blue sky[4] to be closely the same for observations made during various observing runs.

The agreement with the results of other observers is satisfactory. The polarizations observed with the green filter on lunar regions, Mars, Venus, and on Jupiter and its poles are in general agreement with those made visually by Lyot.[8] The present range of wavelengths is greater than that used by other observers, but, whenever observations were made at similar wavelengths, the agreement is good. The numerical agreement with Behr[12,2] on the amount of instrumental polarization of the McDonald 91-cm reflector is close, and that on the interstellar polarization[13,3] is good on the average, as is shown in Fig. 2. The comparison with observations made by Sekera on the sunlit blue sky[14,4] is good, and the same applies to the comparison with the work of Dollfus on Venus.[15,11] Agreement, allowing for phase differences, with the work on Mars by Treanor,[16] by Sobieski,[17] and by Dollfus[15] is seen below in Fig. 10, Section VIII. There is fair agreement with the position angles determined by other observers of interstellar polarization [3]

### IV. *Rayleigh Scattering*

For the study of a complex planetary atmosphere such as that of Venus it appears valuable to study first the simpler case of the molecular scattering of the sunlit blue sky.[4] The polarization of the daytime sky has a maximum near 5500 Å, as is shown in Fig. 3. The decline in the ultraviolet is caused by multiple scattering, while in the infrared it is mostly due to ground reflection that is especially strong when green plants are present. The maximum was found near 75% polarization. The agreement of the Rayleigh-Chandrasekhar theory with the observations is good. The lack of complete polarization appears due to molecular anisotropy (6%), multiple scattering (6%), and ground reflection (5%), while there is a discrepancy between molecular theory and the observations, presumably due to aerosols (8%). At the time of sunrise, the polarization in the infrared was found to be as high as 84%, and

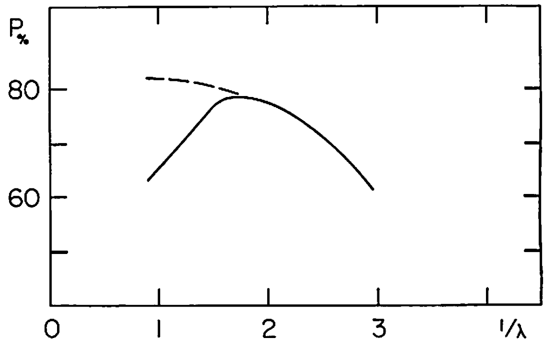

Fig. 3. Polarization of the clear blue sky 90° from the sun, observed on the morning of August 31, 1960, at the McDonald Observatory; with the sun 3° below (broken line), and 4° above the apparent horizon.

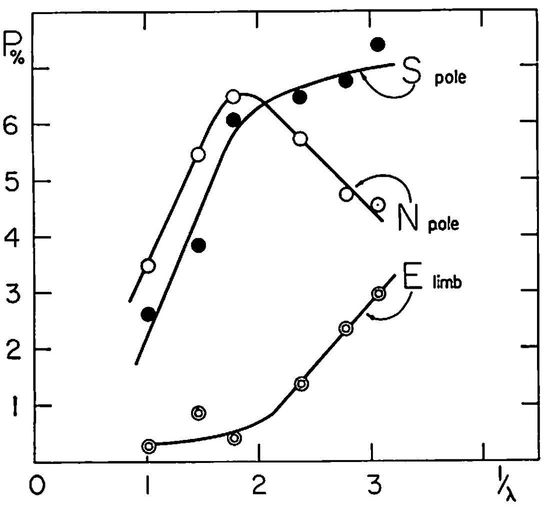

Fig. 4. Polarizations at the South Pole, North Pole, and East limb of Jupiter. Observations made with a 4 sec-of-arc diaphragm, in April 1960.

therefore greater than that in the green and in the ultraviolet. However, within about 20 min after sunrise the polarization in the infrared (for a clear sky but with vegetation around the observatory) was found to drop to 64%, which is appreciably less than the amounts in the green and ultraviolet. During the remainder of the day the polarization of the clear blue sky at 90° phase does not change appreciably.

It appears important to improve further the comparison between the observations and the theory of the sunlit blue sky. Since 1871, when Lord Rayleigh first attempted the comparison, the challenge has been recognized and progress has been made step by step. The main uncertainty presently lies in the unknown reflectivity of the ground and surface haze. We are therefore planning to repeat the measurements from a balloon, in order to include simultaneous measurements of the reflectivity of the ground and surface haze below the balloon. Thus the comparison between observations and the Rayleigh–Chandrasekhar theory may be improved, or a well-observed difference between observations and theory may allow us to determine the scattering by aerosols.

The polarization of the total disk of Jupiter is slight, but at the poles there always is up to 8% polarization, nearly independent of the planetary phase angle. Lyot[8] discovered the anomalous polarization and tentatively explained it by multiple scattering in the molecular part of the Jovian upper atmosphere. Other explanations have at times been proposed in the literature, by a thin fog or by meteoric dust particles. The wavelength dependence of the polarization[5] is shown in Fig. 4; again, as for the sunlit blue sky, the agreement of the Rayleigh–Chandrasekhar theory with the observations is close. Apparently, molecular scattering by the gas above the cloud layers explains the polarizations. From a comparison with the theory it is found that the optical thickness at 5500 Å lies between 0.4 and 0.8.

Effects similar to those for Jupiter have been observed on Saturn. In general, it appears that the wavelength dependence of polarization may be used for the detection of planetary molecular atmospheres. Even at small phase angles the polarization caused by Rayleigh scattering may still be appreciable. Such attempts for the detection of an atmosphere could be made with some effort for Pluto, Triton, Titan, etc. The results on the Jovian satellites I–IV so far have been inconclusive; the main uncertainty lies in scattered light within the telescope and earth's atmosphere from the bright disk of Jupiter.

## V. *Interstellar Particles*

The wavelength dependence of the interstellar polarization is shown in Figs. 2 and 5. Details of this work have been published[3] (plots of two individual stars are in Fig. 3 of ref. 18). The wavelength dependence can be qualitatively interpreted by means of the calculations of van de Hulst (ref. 1, Chap. 15). The particles presumably are conglomerates of some $10^6$ molecules each, the refractive index is about 1.5 (with imaginary component), and the diameters are of the order of $0.6\ \mu$ (although they are not spherical, but rather elongated particles).

The exact nature of the interstellar particles is still unknown as there is a complex set of parameters (e.g., size, refractive index, aspect) each strongly affecting the characteristics one might observe. Extension of the wavelength range of the observations is obviously important. Progress is being made by H. L. Johnson with infrared stellar photometry. It is seen (ref. 1) that an extension to wavelengths shorter than 3000 Å,

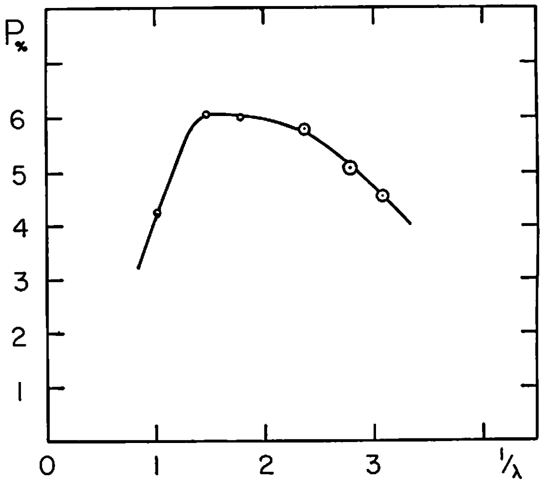

Fig. 5. Normalized average of interstellar polarization, observed on 8 stars that are at various galactic longitudes.

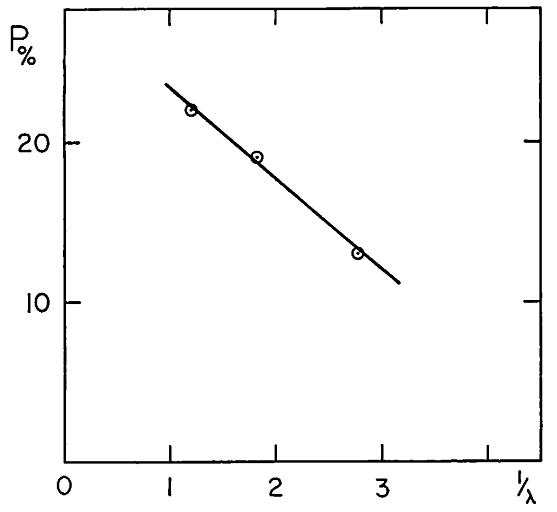

Fig. 6. Polarization in reflection nebulae, observed on small regions in NGC 7023 and NGC 2068.

especially for observations of interstellar reddening, could be especially important in resolving the nature of the particles. The measurements will have to be made at various galactic longitudes since Greenberg and Meltzer[19] have shown that differences in aspect also play a role.

Also on reflection nebulae the wavelength dependence of polarization is an effective tool in the study of interstellar particles. The light is scattered by particles that surround a star, the scattering angles are of the order of 90°, and the polarization phenomena are pronounced. The scattering should be mostly single because of low particle density so that the complications of multiple scattering need not be taken into account. The application of the Mie theory to a sufficient number of parameters of brightness and polarization at different wavelengths may yield the refractive index of the particles, the size, and perhaps even the size distribution. In actual practice it is difficult to observe with many filters at a wide range of wavelengths because the reflection nebulae are faint. The background sky-brightness must be carefully corrected for in order to avoid systematic errors. A preliminary result for two reflection nebulae, NGC 7023 and NGC 2068, is shown in Fig. 6, as obtained with three wide-band filters; the electric-vector maximum is tangential with respect to the illuminating star. The measurements were made with a diaphragm 22 sec of arc in diameter, and we normalized to the amount of polarization at 38 sec of arc northeast of the central star in NGC 7023.

For the intercomparison of the particles between the planets with those between the stars it is important to observe the Zodiacal Light. As to the origin of the Zodiacal Light it is still uncertain whether it is due to scattering by particles or by electrons. The wavelength dependence of polarization, if it can be observed, may give the answer to this question. If no polarization dispersion is found, the Zodiacal Light probably is caused by electron scattering. Appreciable wavelength dependence, on the other hand, probably implies predominant scattering by small particles, and the particle characteristics may then be obtained from a fit of the Mie theory to the observations.

Observations of reflection nebulae and of comet tails are difficult to obtain free of systematic errors because of emission effects. Some of the emissions may be avoided by a choice of proper filters, and then the main problems are sky background and phototube noise.

## VI. *Venus*

The atmosphere of Venus is complicated in that the scattering observed at different wavelengths is caused at different altitudes as well as by different constituents in the atmosphere. Figure 7 shows the percentage polarization as a function of phase, observed between the inferior conjunction of August 1959 and the superior conjunction of June 1960; a preliminary report has been published.[11] The curves are drawn closely through the observations that were made with six filters: Infrared (effective wavelength near 9900 Å), Red (6830 Å), Green (5600 Å), Blue (4200 Å), Ultraviolet (3590 Å), and a filter at 3250 Å, isolated by using a Nickel-sulfate solution. The scatter of the Venus observations about the mean curves corresponds to the observational precision (±0.055% p.e.), which indicates that Venus is remarkably steady from night to night. The N-curve is given with a dashed line so as to indicate that it has not yet been as well established as the other curves. The uncertainty may, however, be intrinsic in that the polarization of Venus at short wavelengths may be irregularly variable.

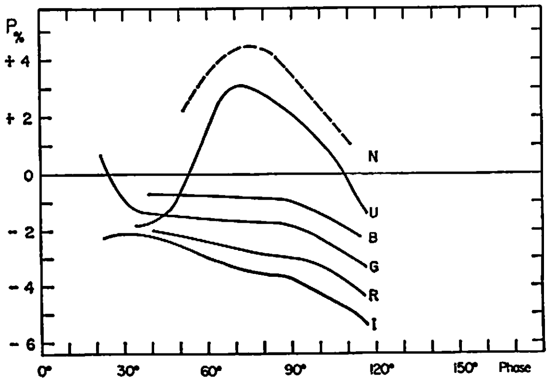

Fig. 7. Polarization of the total disk of Venus, as a function of phase: from 117° on October 8, 1959, until 19° on May 3, 1960. Observations with Infrared, Red, Green, Blue, and Ultraviolet filters, and with a filter near 3250 Å that uses a Nickel-sulfate solution.

The polarization at longer wavelengths is negative, that is, with the electric-vector maximum in the plane of the ecliptic. Predominant in visual light and at longer wavelengths probably is the scattering by large (micron-size) particles, crystals, or droplets. The polarization in the ultraviolet is entirely different, it has the electric-vector maximum perpendicular to the ecliptic and the phase dependence is strong. Predominant in the ultraviolet probably is molecular scattering or scattering by very small particles, or both.

Observations are needed at the shortest possible wavelengths, and they may be obtained with high-altitude balloons (*viz.* Section IX). With measurements made at wavelengths shorter than 3250 Å, it is expected that a detailed fit to the Rayleigh-Chandrasekhar theory will account for the contribution by the molecular scattering. The residuals will then be explained as due to the scattering by particles, and they may be compared with the Mie theory so as to obtain a determination of refractive index and particle sizes.

The range of wavelengths should be extended also into the far infrared. Since Venus is bright, the lack of sensitive detectors is not serious, and we are planning polarization measurements at 1.3, 2.2, and 3.6 $\mu$. Beyond 3 $\mu$ there apparently are strong absorptions in the atmosphere of Venus, as the brightness of Venus at 3.6 $\mu$ is magnitudes fainter than that at shorter wavelengths.[20]

### *VII. The Moon and the Asteroids*

Mercury, the asteroids, and most of the satellites, form a special category because of the lack of a molecular atmosphere. They may have a surface layer of fine particles, but effects of multiple scattering and of the background may complicate the phenomena. In preparation is a paper with observational results on colors and polarization of seven small regions on the surface of the moon over a large range of phase and also closely before and after a lunar eclipse. The observations were mostly made at the Cassegrain focus of the 208-cm McDonald telescope, and the lunar regions have a diameter of the order of 4 sec of arc. A preliminary result, published previously,[18] on one of the seven regions is given in Fig. 8, while the wavelength dependence is shown in Fig. 9.

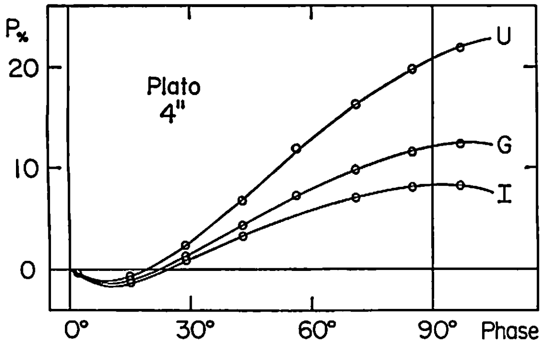

Fig. 8. Polarization of a 4 sec-of-arc region at the bottom of lunar crater Plato, as a function of phase. Observations made with the McDonald 82-in. (208-cm) telescope, April 23–30, 1959, with Ultraviolet, Green, and Infrared filters.

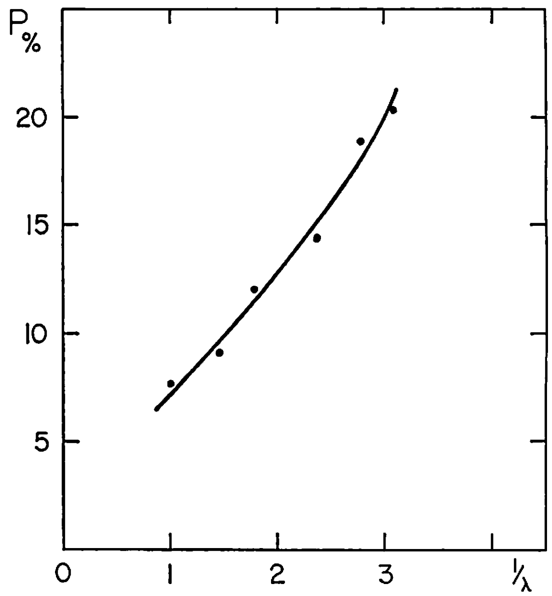

Fig. 9. Polarization of Mare Crisium near 90° phase.

Polarimetry is useful for intercomparisons between the surface of the moon and that of the asteroids, especially when combined with laboratory measurements.[8,15] Lyot concluded that the moon is covered with small particles having diameters of the order of 1 $\mu$, for example, lava dust. This conclusion should not be misinterpreted as a proof of the existence of lava dust on the lunar surface, because other fine particles may give the same results. The choice of particles may be narrowed down by obtaining the parameters of polarization and intensity, both simultaneously, over a wide range of wavelength and phase.

As for the light variations of the asteroids one problem has not yet been solved. Is the brightness variation with rotation due to change of the projected area, that is, due to the shape of the asteroid, or is it due to the asteroid's body having different albedo at different parts of the surface, or to both? Polarimetry may give the answer to this question. It is known for the lunar surface that the dark areas have a larger amount of polarization than the bright areas. If the same is true on the asteroids, we would be able to observe a change in the amount of polarization with rotational phase. That is, as the asteroid is brighter, the polarization would be less, etc. A polarization curve would be observed as well as a light curve. Provin started this type of study and found little polarization–time variation for Iris.[15] It is essential, however, to obtain the brightness–time variation simultaneously. Because of aspect variation Iris may have had small light curve amplitude at the time of Provin's polarization measures.[21] Our first polarization attempts have also given inconclusive results, which may mean that the bodies of the asteroids have rather uniform albedo over the surface and that the observed brightness variations are due to shape only. However, this is no more than a preliminary conclusion and further work is especially valuable on an asteroid with large amplitude of light variation and at large phase angle.

### *VIII. Miscellaneous Measures*

A few miscellaneous measures are given in Table I. The phase angle is the angle subtended at the object between the radius vectors to the sun and earth. In addition to $P$, the percentage polarization, the position angle, $\theta_r$, is given which is the position angle of the electric-vector maximum with respect to the normal to the plane through object-sun-earth (position angles are usually given between 0° and 180° only). The observations on comet Burnham are preliminary; a wide diaphragm was used, centered on the nucleus; no correction was made for emission effects. Colons in Table I indicate low quality of observation.

TABLE I. MISCELLANEOUS POLARIZATIONS

| Object | Date U.T. | Phase angle (deg) | $1/\lambda$ | $P$ (%) | $\theta_r$ (deg) |
|---|---|---|---|---|---|
| Comet Burnham (1959 k) | 60.05.02 | 65 | 1.20 | 14.6 | 1 |
| | 60.05.04 | | 1.20 | 14.4: | 178: |
| | 60.05.03 | | 1.82 | 8.9: | 171: |
| | 60.05.03 | | 2.38 | 8.3 | 5 |
| | 60.05.06 | | 2.38 | 6.7: | 177: |
| | 60.05.03 | | 2.78 | 8.4: | 7: |
| Mars | 59.04.24 | 33.4 | 1.01 | 1.08 | 1.4 |
| | | | 1.79 | 1.83 | 178.8 |
| | | | 2.79 | 6.88: | 0.7 |
| | 59.04.25 | 33.3 | 1.01 | 1.05 | 3.5 |
| | | | 1.79 | 1.65 | 1.8 |
| | | | 2.79 | 6.74: | 179.6 |
| | 59.04.28 | 32.9 | 1.01 | 1.00 | 4.2 |
| | | | 1.79 | 1.72 | 178.7 |
| | | | 2.79 | 6.32: | 179.1 |
| | 59.08.04 | 8.0 | 1.46 | 0.89: | 116.2: |
| | | | 2.38 | 0.53: | 94.6: |
| | 59.08.10 | 7.4 | 1.01 | 0.38 | 149.2 |
| | 60.08.18 | 43.2 | 1.01 | 3.15 | 0.4 |
| | | | 1.79 | 3.47 | 2.0 |
| | 60.08.22 | 43.3 | 1.46 | 2.49: | 7.7: |
| | | | 2.38 | 4.93: | 4.1: |
| | | | 3.08 | 1.52: | 1.7: |
| | 60.08.23 | 43.3 | 1.01 | 2.52 | 179.2 |
| | | | 1.79 | 3.28 | 3.2 |
| | | | 2.79 | 0.06 | 1.4 |
| | 60.08.29 | 43.4 | 1.46 | 1.70 | 178.9 |
| | | | 2.38 | 4.28 | 5.7 |
| | | | 3.08 | 9.80: | 2.2 |
| | 61.03.17 | 36.1 | 1.01 | 1.53 | 12.4 |
| | | | 1.79 | 1.94 | 175.9 |
| | | | 2.79 | 7.56: | 172.2 |
| Mercury | 59.12.04 | 111 | 1.01 | 6.7 | ... |
| | 59.12.09 | 86 | 1.46 | 7.09 | ... |
| | 59.12.04 | 111 | 1.79 | 8.0 | ... |
| | 59.12.09 | 86 | 2.38 | 8.7 | ... |
| | 59.12.04 | 111 | 2.79 | 9.4: | ... |
| | 59.12.09 | 86 | 3.08 | 11.1: | ... |
| | 61.11.10 | 73 | 1.01 | 5.91 | 179.0 |

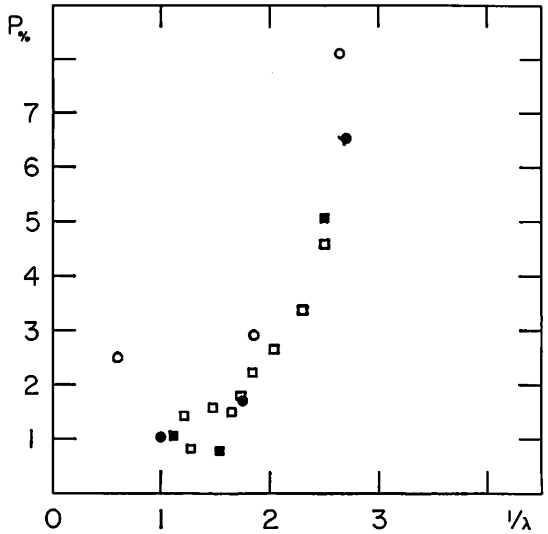

Fig. 10. Polarization of Mars, observed by: Dollfus, near 35° phase, 1949/1950 (open squares); Treanor, at 35°.5 phase, May 1961 (filled squares); Sobieski, at 36°.4 phase, March 1961 (open circles); and in the present program, near 33° phase, April 1959 (filled circles).

Mars has an increasing amount of polarization toward shorter wavelengths, as was discovered by Dollfus.[15] A similar wavelength dependence of the polarization was observed by P. J. Treanor[16] with interference filters at eight wavelengths from 4000 to 9000 Å. In addition, Treanor found that, to the red of 6500 Å, the polarization increases slightly. A minimum near 0.8 $\mu$ is also confirmed by very preliminary measures (not plotted in Fig. 10) made by S. Sobieski.[17] In Fig. 10, we plotted our observations and those by Dollfus, Treanor, and Sobieski. Even though these observations were made at different dates and phases, the polarization dispersions are closely the same. Dollfus[15] has explained the wavelength dependence of the polarization by the presence of the Martian atmosphere.

Mercury was found to have approximately the same wavelength dependence as that of the lunar surface. The measurements are difficult, especially at shorter wavelengths, because of the proximity to the sun.

An attempt was made to discover polarization of the flare-star system Krüger 60, during the time of no-flare, but the results are inconclusive. No polarization greater than 0.4% was detected. At the request of K. Aa. Strand, we also checked for possible light-variations during the time of no-flare. Krüger 60 was observed with respect to a near-by star from $1^h30^m$

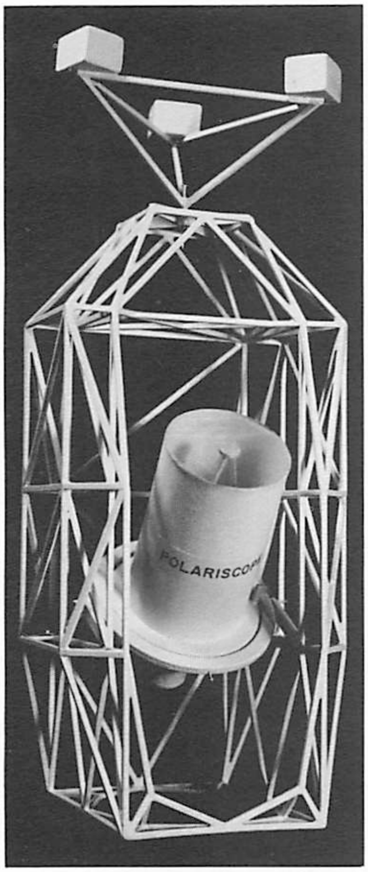

Fig. 11. Balsa-wood model of balloon gondola with 28-in. (71-cm) telescope.

until $8^{\mathrm{h}}50^{\mathrm{m}}$ on 19 October 1958 Universal Time. No brightness fluctuations were detected as the average deviation of individual measures from the mean light-level was ±0.005 mag, equal to the precision of such observations.[21] We would like to thank Dr. Strand for the loan of photometer equipment during the early stages of this program.

## IX. *Balloon Programs*

We are presently preparing a balloon program, Project Polariscope, supported by the National Science Foundation, with the first flights scheduled for 1963. A model of the gondola and telescope system made by M. Diels is shown in Fig. 11. Figure 12 shows a diagram of the optical system. The primary is a 71-cm fused silica mirror, $f/2$; the Cassegrain focus operates at $f/13$ (Dall-Kirkham optics).

In addition to the system of Fig. 12, there is mounted a wide-angle polarimeter designed by a group working with Z. Sekera (see below), and a small telescope for photoelectric guiding. The attitude control is expected to hold to within ±20 sec of arc. The total weight of the system is of the order of 700 kg, and with a $10^7$ ft$^3$ ($3 \times 10^5$ m$^3$) balloon the estimated ceiling is near 35.4 km altitude. We are planning the following programs.

### *A. The Earth's Atmosphere and Albedo*

In close collaboration with Z. Sekera of the University of California at Los Angeles, the relative intensity and the polarization at 5° intervals in the sun's vertical circle will be measured at various altitudes up to 35.4 km and over the greatest possible range of wavelengths. The telescope will be pointed below as well as above the gondola (except for 25° zenith distance obscured by the balloon). The main purposes are: (1) to obtain as closely as possible an intercomparison of the observations on the sunlit sky with the Rayleigh-Chandrasekhar theory (*viz.* Section IV); (2) to extend the study to that of aerosols in the earth's atmosphere; and (3) to determine reflectivities of clouds and of various parts of the earth's surface.

### *B. Measurements at Wavelengths Shorter than 3000 Å*

The need for observations of the interstellar polarization and reddening and of polarization of the planet Venus at wavelengths shorter than 3000 Å is discussed in ref. 22 and in Sections V and VI of this paper. J. V. Dave recently supplied calculations of the attenuation due to molecular scattering, ozone, and oxygen above 33.5 km altitude. The calculations are based on measurements during rocket flights[23] and on Tables 16-15, 16-16A, and 16-17 of the *Handbook of Geophysics*[24] (a factor 0.98 was used to obtain absorption coefficients for ozone at 245°K instead of the 291°K in the *Handbook*). With Dave's data, we compiled in Table II the extinction, in astronomical magnitudes $\Delta m = 2.5 \log_{10} I_1/I_2$, as a function of wavelength. The present calculations were made for latitudes near +35°. (We are indebted to Dr. Dave for his advice.) Wavelength intervals of 100 Å are used, and the calculations are for three altitudes, namely, 33.5, 36.6, and 39.6 km. The results are in general agreement with calculations previously obtained by other authors (see, for instance, ref. 25). The attenuations of Table II are typical values; above 33.5 km, the ozone concentration is less during the winter than during the summer. However, under unfavorable ozone conditions the totals in Table II may be greater by several magnitudes. A detailed analysis was made of the limiting magnitude of our polarimeter with a 71-cm

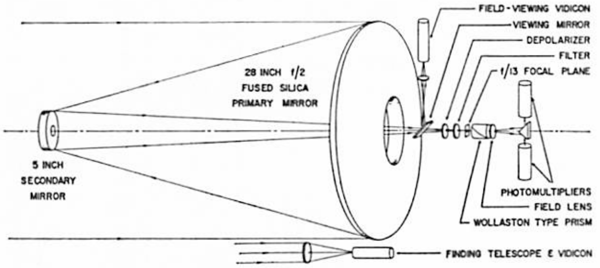

Fig. 12. Diagram of the 28-in. (71-cm) balloon telescope, the polarimeter, and the vidicons.

TABLE II. ATTENUATIONS AT HIGH ALTITUDES

| | | Extinction, in magnitudes at sec$z$ = 1, at | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Altitude | Constituent | 2050 Å | 2150 Å | 2250 Å | 2350 Å | 2450 Å | 2550 Å | 2650 Å | 2750 Å | 2850 Å | 2950 Å |
| 110,000 ft<br>33.5 km<br>20.8 miles | Scattering | 0.05 | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 |
| | Oxygen | 0.73 | 0.33 | 0.17 | 0.10 | 0.04 | — | — | — | — | — |
| | Ozone (winter) | 0.05 | 0.14 | 0.48 | 0.87 | 1.37 | 1.59 | 1.37 | 0.83 | 0.36 | 0.20 |
| | Ozone (summer) | 0.21 | 0.58 | 1.67 | 3.56 | 5.59 | 6.52 | 5.59 | 3.40 | 1.48 | 0.47 |
| | Sum (winter) | 0.83 | 0.51 | 0.68 | 0.99 | 1.43 | 1.61 | 1.38 | 0.84 | 0.37 | 0.21 |
| | Sum (summer) | 0.99 | 0.95 | 1.87 | 3.68 | 5.65 | 6.54 | 5.60 | 3.41 | 1.49 | 0.48 |
| 120,000 ft<br>36.6 km<br>22.7 miles | Scattering | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | Oxygen | 0.56 | 0.25 | 0.13 | 0.08 | 0.03 | — | — | — | — | — |
| | Ozone (winter) | 0.03 | 0.09 | 0.25 | 0.53 | 0.83 | 0.96 | 0.83 | 0.50 | 0.22 | 0.07 |
| | Ozone (summer) | 0.17 | 0.45 | 1.32 | 2.80 | 4.40 | 5.13 | 4.40 | 2.68 | 1.16 | 0.37 |
| | Sum (winter) | 0.63 | 0.37 | 0.40 | 0.63 | 0.88 | 0.97 | 0.84 | 0.51 | 0.23 | 0.08 |
| | Sum (summer) | 0.77 | 0.73 | 1.47 | 2.90 | 4.45 | 5.14 | 4.41 | 2.69 | 1.17 | 0.38 |
| 130,000 ft<br>39.6 km<br>28.4 miles | Scattering | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | Oxygen | 0.38 | 0.17 | 0.09 | 0.05 | 0.02 | — | — | — | — | — |
| | Ozone (winter) | 0.02 | 0.04 | 0.12 | 0.26 | 0.41 | 0.48 | 0.41 | 0.25 | 0.11 | 0.03 |
| | Ozone (summer) | 0.12 | 0.31 | 0.90 | 1.92 | 3.01 | 3.51 | 3.01 | 1.83 | 0.80 | 0.25 |
| | Sum (winter) | 0.42 | 0.23 | 0.23 | 0.32 | 0.44 | 0.49 | 0.42 | 0.26 | 0.12 | 0.04 |
| | Sum (summer) | 0.52 | 0.50 | 1.01 | 1.98 | 3.04 | 3.52 | 3.02 | 1.84 | 0.81 | 0.26 |

telescope and with wide-band filters using selected photomultipliers. It appears possible, even during the most unfavorable ozone concentration, to observe the brighter stars and planets at 2200 Å, at altitudes above 33.5 km.

### C. *Other Studies*

With a 71-cm balloon telescope there is a host of possible studies, such as: narrow-band photometry on absorption features due to water vapor, etc., in planetary atmospheres; ultraviolet and infrared photometry and spectroscopy; studies of cloud formations; polarimetry of the Zodiacal Light at various wavelengths; etc. If we do not lose the system in flight, it will be flown repeatedly, and also for programs of other investigators.

## X. *Polarimeters for Unmanned Spacecraft*

The polarimeter/photometer of Fig. 12 may serve as a "pilot model" for space telescopes such as the NASA Orbiting Astronomical Observatories and those of the Kitt Peak National Observatory. Experience will be gained during the balloon flights with data acquisition, telemetry, etc.

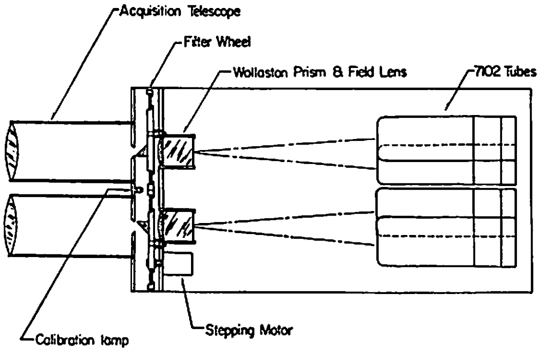

Fig. 13. A lightweight polarimeter/photometer for MARINER-type space probe.

Another type of polarimeter, shown in Fig. 13, was designed for lightweight planetary probes. The advantage of making polarization measures from a space probe lies in the possibility of making a detailed scan of the surface of the planet due to the close approach by the probe to the planet. Also, especially for Mars, large phase angles are possible by choice of a suitable fly-by. In principle the photometer is similar to the one used by us with telescopes on the ground; the modifications are dictated by weight limitations, by the automation, and by the need to have few moving parts. The design consists of two adjacent telescopes, two diaphragms, the filter and calibration wheels, the field lenses ("Fabry lenses"), the Wollaston prisms, and the phototubes.

The total weight of this system is under 4.5 kg, it is about 40 cm long, and it requires less than 5 W of power. Approximately the following effective wavelengths are proposed: 2900, 3500, 4300, 5600, 6900, and 9900 Å (having nearly equal spacings in $1/\lambda$). The prisms are calcite Wollastons, with butyl methacrylate cement; an alternate solution is to have ammonium di-hydrogen phosphate (ADP) with the halves in optical contact. Transistorized electrometer-type operational amplifiers accept the photocurrents, and a programmer follows the output of each phototube and pulses the stepping motor for rotation of the filter wheel after each observation. The disk of Mars, for instance, could be scanned at the rate of once per minute; the scans are proposed to be over the center of the planetary disk, with the scans in the direction of the motion of the space probe.

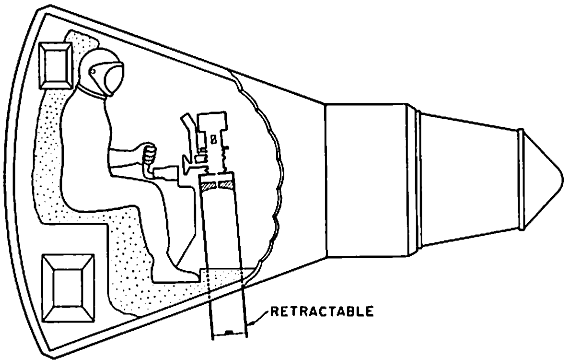

Fig. 14. The MERCURY capsule with a photometer/polarimeter instead of the original MERCURY periscope.

The space-probe polarimeter of Fig. 13 will be flown and used on board the balloon gondola described in Section IX. The special application on board the space probe will, of course, require detailed technical studies imposed by the environment and by the integration of the polarimeter with the space probe. The telemetry of the commands and observations will be a part of the general system of the probe.

## *XI. A Polarimeter for Manned Spacecraft*

The polarimeter that we have used extensively with telescopes on the ground can be used, after relatively minor modifications, in manned observations in a balloon gondola (e.g., the Stratolab gondola of the U.S. Navy), and in manned spacecraft (f.i., the Mercury, Gemini, and Apollo capsules). A sketch of such an arrangement is given in Fig. 14, while the details of the photometer are shown schematically in Fig. 15; the knobs will actually be at right angles to the eyepieces.

In 20 min or so the astronaut can make a set of measurements of polarization, photometry, and photography of Venus, for instance, at two or three different wavelengths in the extreme ultraviolet. A preliminary reconnaissance has been made of the engineering problems for mounting a polarimeter on board the Mercury capsule. (We are indebted to A. E. Lombard and M. Witunski of the McDonnell Aircraft Corporation for their technical assistance.) The most serious problem probably is that of close attitude control (±8 min of arc). It is, of course, of the greatest importance to make the photometer lightweight. The expected power requirement, 16 W or less, does not appear prohibitive.

## *XII. Concluding Remarks*

Polarimetry is a powerful tool applicable to a wide range of subjects. A variety of techniques is possible, and they need not be complicated. We have not as yet undertaken a study of elliptical polarization; such a study appears to be an important challenge. No polarization-wavelength measurements have as yet been made of synchrotron radiation, for instance in the Crab Nebula. There is also a lack of polarization experiments in the laboratory. Lyot's laboratory work was done in visual light only, and progress may be expected from an extension to the greatest possible range of wavelengths.

This program has been supported by grants from the Office of Naval Research to Indiana University and to the University of Arizona. The following people have worked with us: S. F. Pellicori in the Electronics Shop; R. E. Samuelson, H. J. Wood, and A. U. Landolt at the telescopes; E. C. Olson and D. Fischel programmed routines for IBM 650 and IBM 709, respectively; and Mrs. D. J. Owings has made nearly all of the reductions. We would also like to acknowledge the cooperation of the Research Computing Center of Indiana University.

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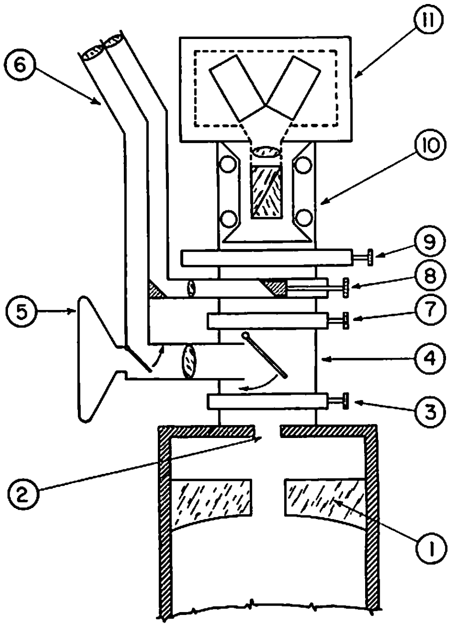

Fig. 15. Components of the photometer/polarimeter of Fig. 14: (1) 8-in. (20-cm) Cassegrain $f/10$ telescope; (2) quartz pressure-port; (3) Lyot depolarizer; (4) viewing mirror; (5) camera; (6) eyepieces, schematically drawn; (7) diaphragms; (8) viewing prism; (9) filters; (10) rotating assembly for Wollaston prism, field lens, and (11) electrically refrigerated phototubes.

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