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PHOTOELECTRIC OBSERVATIONS OF MARS AND JUPITER WITH A SCANNING POLARIMETER

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INTRODUCTION

Nearly forty years have passed since Lyot (1929) published his classic polarization measurements of the moon and planets. These observations were secured with a visual polarimeter which he developed; a modified version of this device is still in use. The observations are of high accuracy, but were often made only in the plane of vision, which includes the planet, earth, and sun, or in the plane perpendicular to it. Furthermore, the areas measured on the planet were usually not accurately defined and in at least some cases included a large portion of the entire planetary disk.

During the past fifteen years many polarization observations of Mars have been made, visually, photographically, and photoelectrically, and in a number of spectral regions. Among those who have made important contributions in this way are A. Dollfus (1966), J. H. Focas (1967), O. R. Golosejevo (1967), A. V. Moroshenko (1964), and D. L. Coffeen (1968). The observations all show polarization vectors which, similar to those in the case of the moon, are highly phase-dependent and either parallel or perpendicular to the intensity equator, which is the plane containing Earth, Mars and Sun.

In contrast with the many studies of Mars, the number of polarization observations of Jupiter published since Lyot's dissertation are relatively few. Some have been obtained by Y. Ohman (1944), by Dollfus (1957) and by O. R. Bolkvadze (1967).

The observations to be presented in this paper should have high resolution, and the areas under observation at any time are accurately defined. A brief description of the method may be found on Page 61 of this volume (Hall, 1968). Although the seeing was usually poor and the equipment was not yet operating at its peak performance near the time of opposition of Mars in the spring of 1967, it seems desirable to present the Mars observations here in order to indicate the advantages of this technique. Such advantages should be more apparent, however, from an inspection of the observations of Jupiter which were made a year later.

In the following discussion all directions are those as they would appear to an observer on the earth (astronomical convention) and not those as seen by an observer on the planet. The electric vectors of the polarized light are plotted from North through East.

The polarimeter was used on either of two reflectors. One was the 72-inch Perkins telescope of the Ohio Wesleyan and the Ohio State Universities at the Lowell Observatory. The other was a Cassegrain combination of a 30.5 spherical primary and a specially-figured F/32 secondary; this combination should produce sharp focal-plane images on the optical axis and stellar images of about one second of arc at a distance of one minute of arc from the optical axis. The scales of the 72-inch and 30-inch telescopes are 6.5 and 8.5 arc seconds per millimeter, respectively.

Numerous scans using a depolarizer have shown very low (less than 0.3 percent) residual polarization for each telescope in both the ultraviolet and visual regions. Measures of "unpolarized" stars at both telescopes have indicated a residual polarization comparable to that to be expected on the basis of the finite number of counts involved. A brief description of the statistical errors to be expected on the basis of the number of counts has been presented by A. Elvius (1968).

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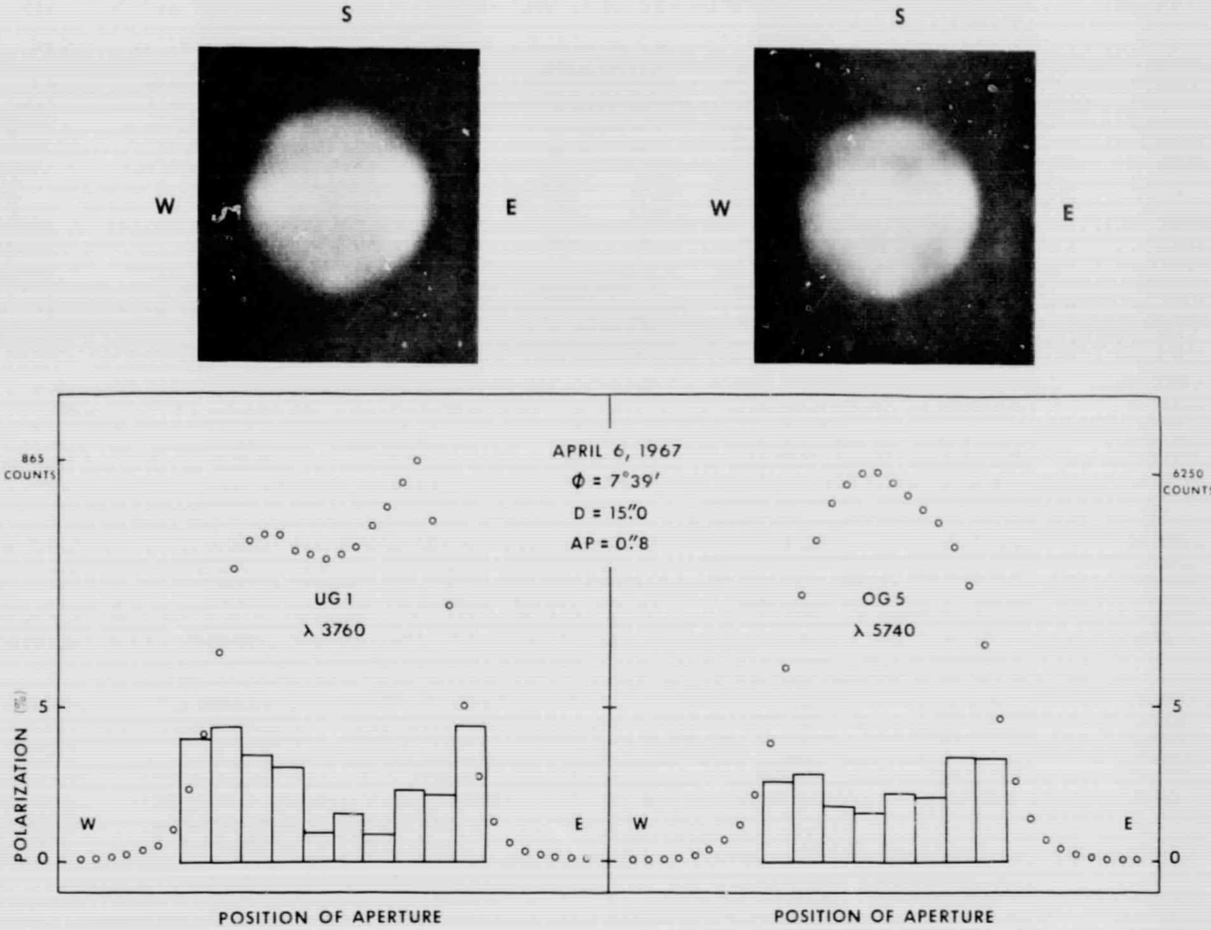

Figure 1. Intensity scans along the equatorial zone of Mars made on April 6, 1967. The polarization observed is indicated by the histograms. The phase angle of Mars was 7.6 degrees, its apparent diameter 15.0 arc seconds, and the aperture 0.8 arc seconds. In both wavelength regions the clouds at the limbs show the most polarization. The photographs were obtained in the blue and yellow regions with the Lowell 24-inch refractor near the time when the observations below them were obtained.

MARS

During the 1967 opposition, both polar and equatorial scans were made of Mars with Schott filters centered at λ3760 (UG 1) and at λ5740 (OG 5). Figure 1 shows the results of equatorial scans obtained at the 30-inch reflector on April 6. The open circles represent the average of two adjacent elements of light intensity measured by one multiplier at one of the four position angles of the polarimeter; the histograms give the average values of the observed polarization. The photographs of the planet above each diagram were taken with the 24-inch Lowell refractor near the time of the observations. These reveal clouds on the east and west limbs which produced more polarization than the central regions of the planet in both ultraviolet and yellow light.

All polar scans made in ultraviolet light from April 1 to July 20 are shown in Figure 2, and similar scans made in the yellow, in Figure 3. Average values of the polarization are designated by open circles. The length of each diametral scan of Mars was usually divided into 50 elements of information, and average values of the polarization along the scan line were computed for a number of successive elements. For example, for the Mars equatorial scan of April 6, the statistical accuracy (mean error) obtained by combining the information in every four successive channels across the disk was near 0.4 percent for OG 5 and about 1.2 percent for UG 1. The toes of the curves have much larger errors because of the much lower light intensity and the correspondingly fewer counts.

Since the polar diameter of the planet varied considerably throughout the observational period, the curves have been drawn for Figures 2 and 3 so as to extend over about the same distance along the base line. Except for the 72-inch observations of

FILTER UGI (λ=3760A)

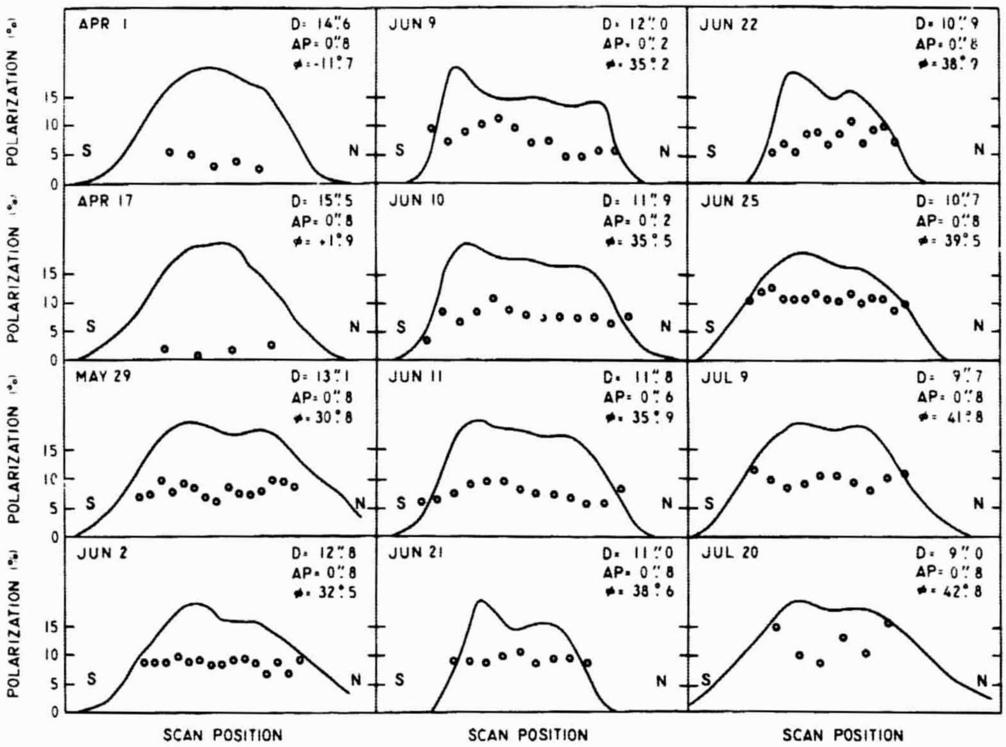

Figure 2. Scans of Mars made in ultraviolet light on 12 nights near its 1967 opposition. The curves are observed intensities as the aperture scanned the Martian disk from the south to the north pole, and the circles represent the observed polarization.

FILTER OG5 (λ=5740A)

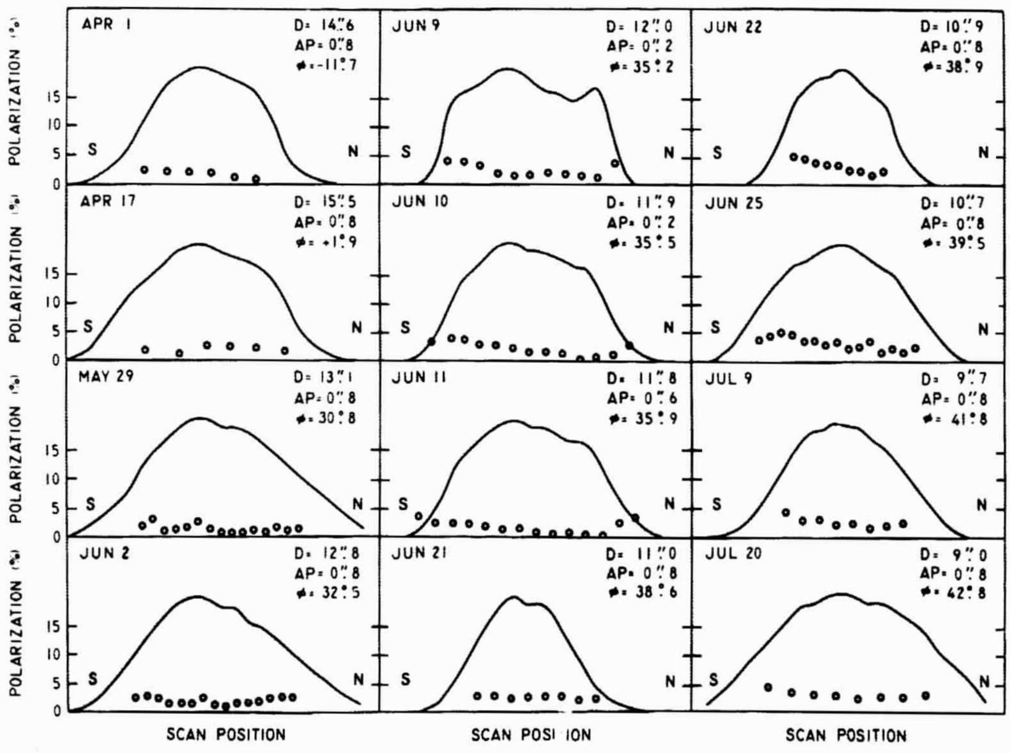

Figure 3. Polar scans of Mars similar to those in Figure 2, but made in visual light.

June 9, 10 and 11, all measures were made at the 30-inch reflector. The slopes at the extremities of the intensity curves are a good measure of the image sharpness: the best seeing at the 72-inch was on June 9, and at the 30-inch on June 21 and 22.

Whenever there was significant brightening near the south pole, the degree of polarization observed at this pole appeared to be lower in the ultraviolet than at middle latitudes. However, the polarization in the yellow at the south pole is somewhat higher than at the middle latitudes; a result which agrees with the visual observations of Lyot. A comparison of Figures 2 and 3 shows the well-known fact that the polarization in the ultraviolet is much larger than in the visual.

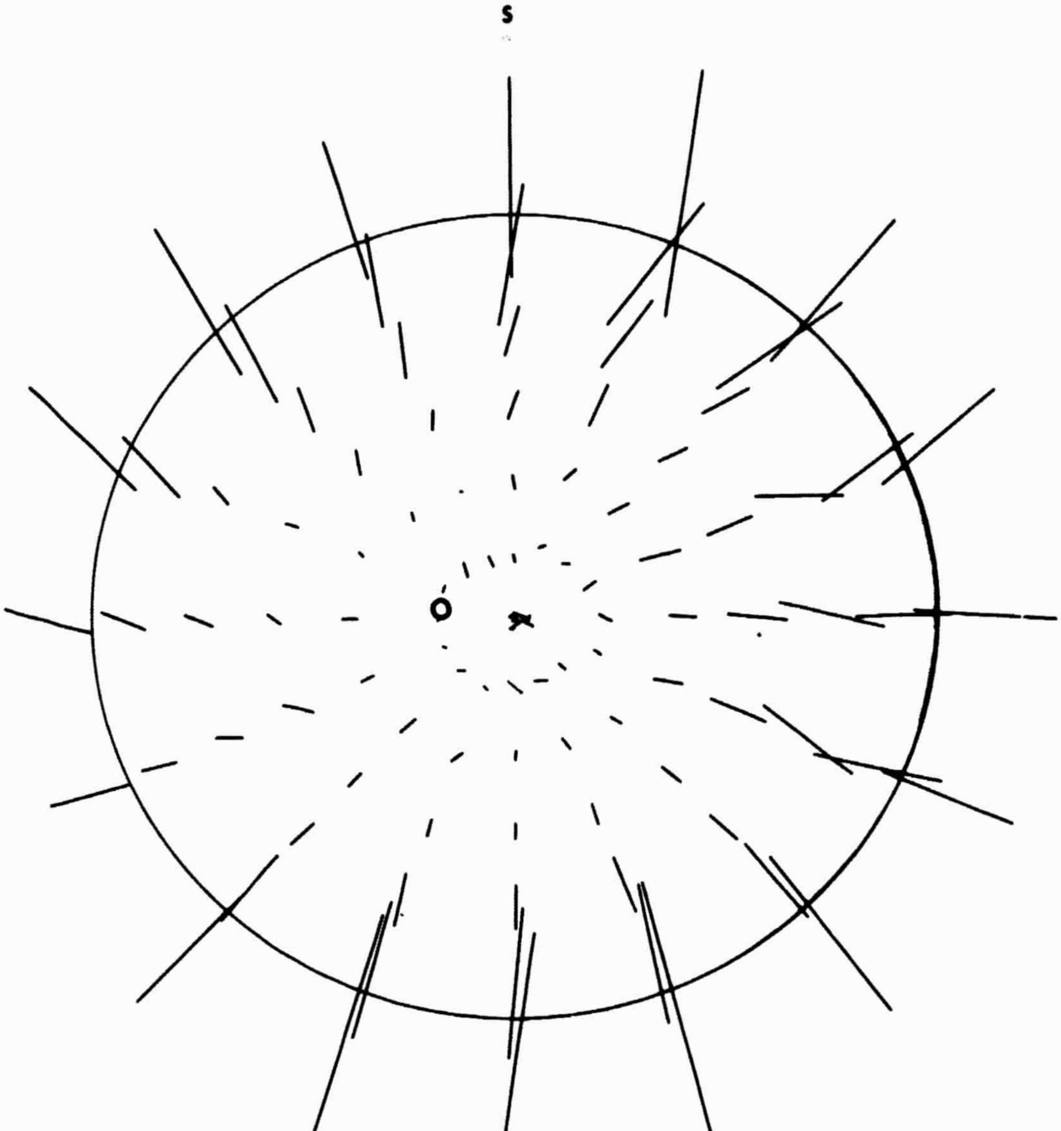

Figure 4. Polarization measures of Jupiter obtained with the 72-inch Perkins telescope on April 24, 1968. The average of the Stokes parameters of five consecutive elemental measures along a single scan line are used to obtain the information at each of the 97 points. The directions of the lines indicate the planes of the electric vector maxima and the lengths of the lines indicate the percentage of polarization on the scale given in the corner of the diagram. All data were obtained in the ultraviolet at an effective wavelength near λ3760. The focal plane aperture was 0.6 arc seconds in diameter. The subsolar point is indicated by the small circle near the center of the diagram and the optical boundary of the planet is designated by the large ellipse. The measures made beyond this boundary contain relatively few counts and have less weight than the other points.

TABLE I

Polarization Observations of Jupiter Made in the Ultraviolet on April 24, 1968

Scanner	W-E 03:55		WNW-ESE 03:40		NW-SE 04:20		NNW-SSE 03:00	
Position	P(%)	P. A.	P(%)	P. A.	P(%)	P. A.	P(%)	P. A.
1	3.0	96°	2.8	127°	5.9	158°	8.4	4°
2	1.5	90	1.3	125	3.1	161	4.8	6
3	1.1	90	0.9	112	1.2	153	1.9	10
4	0.6	78	1.1	100	0.8	157	0.6	9
5	0.6	119	0.5	143	0.7	150	0.5	146
6	0.1	164	0.1	69	0.3	106	0.2	56
7	0.3	181	0.5	94	0.4	86	0.2	40
8	0.6	85	0.6	145	0.3	106	0.2	128
9	1.1	105	1.4	125	0.8	141	0.6	154
10	2.0	106	1.7	134	1.1	139	1.5	177
11	3.8	98	3.1	113	1.9	140	2.9	163
12	3.6	114	3.9	147	5.2	146	5.3	160
13	4.9	108°	5.1	150°	6.3	160°	8.5	13°

Scanner	N-S 04:30		NNE-SSW 04:50		NE-SW 05:00		WSW-ENE 0[illegible]:12	
Position	P(%)	P. A.	P(%)	P. A.	P(%)	P. A.	P(%)	P. A.
1	8.7	14°	10.1	38°	6.8	60°	5.2	69°
2	5.1	17	4.9	35	3.4	63	2.8	65
3	1.5	22	2.0	45	1.3	73	0.8	61
4	0.6	23	0.8	40	0.9	77	0.5	96
5	0.3	16	0.4	60	0.4	80	0.3	71
6	0.6	69	0.5	115	0.3	74	0.3	174
7	0.4	68	0.6	148	0.3	27	0.5	81
8	0.3	32	0.4	54	0.6	38	0.3	77
9	0.5	33	0.1	115	0.4	44	1.1	102
10	1.1	2	0.8	21	0.9	32	2.1	89
11	1.9	6	1.9	31	1.6	43	3.8	74
12	4.9	12	3.2	33	3.7	50	4.5	100
13	6.8	23°	4.9	41°	5.8	54°	4.6	90°

JUPITER

Polarization measurements were made of Jupiter on eleven nights in 1968. On seven of these nights, the 72-inch reflector and a scanning circular aperture of 0.6 arc seconds diameter were used, and on the remaining nights the 30-inch, with a circular aperture of 1.7 arc seconds.

Observations In The Ultraviolet On one night, diametral scans in the ultraviolet were made systematically during a two-hour period at eight different position angles 22.5 degrees apart. These data, obtained with the 72-inch, are given in Table I. The times of observation (U.T.) and the direction of each set of scans with respect to Jupiter's cardinal points are shown at the top of each column. The observed angles of polarization are given with respect to the earth's equatorial system. To reduce these angles to Jupiter's equatorial system one must subtract 22 degrees from the tabular values.

The polarization at 97 points along these scans is plotted in Figure 4; where the center of each vector represents the mean of five consecutive scan elements. The ellipse representing the visible disk of Jupiter conforms in size and shape to ephemeris data. The terminator, on the east limb, is indicated by the shading; the phase angle was 10 degrees. Because of the effects of seeing and the finite size of the aperture, measurable energy was obtained outside the actual disk. Consequently, the centers of the 16 polarization vectors which correspond to this energy are outside the ellipse. Since at these points the light intensity was very much less than on the disk itself, the statistical error of the degree of polarization (based on the number of counts) was about 0.8 percent for the marginal regions but is 0.3 percent across the center of the disk. For a polarization of 6 percent these two figures would correspond to errors in position angle of 3.8 and 1.4 degrees, respectively; if the polarization were 1 percent, the corresponding position angle errors would be 23 and 9 degrees. Measures made on other nights along the same scan lines but in the opposite sense did not reveal any systematic differences.

Figure 5 contains examples of the intensity curves used in computing the polarization vectors shown in Figure 4, together with histograms showing the degree of polarization, usually averaged over five consecutive elements of the scan line. The accompanying photograph of Jupiter was taken at New Mexico State University Observatory in blue light at the same time as the NNW-SSE scans were being run at the Perkins telescope.

The three histograms which correspond to the equatorial scan and its two adjacent scans (shown in the left "column" of Figure 5), indicate that the polarization at the terminator was definitely larger than that on the west limb. This is more clearly exhibited in Figure 6 by the W-E data derived from all scans made in the ultraviolet. With reference to the subsolar point, the degree of polarization on the east is comparable to that on the west. This same trend is also exhibited by the lines of equal polarization shown in Figure 7.

The north-south scan and the two adjacent scans (column at right in Figure 5) show that the polarization near the north limb is, within error of measurement, the same as that near the south limb. The more extensive data in Figure 6 also indicate that the north-south polarization is symmetrical with the center of the disk.

The polarization in the darkest bands does not differ appreciably from that found in adjacent

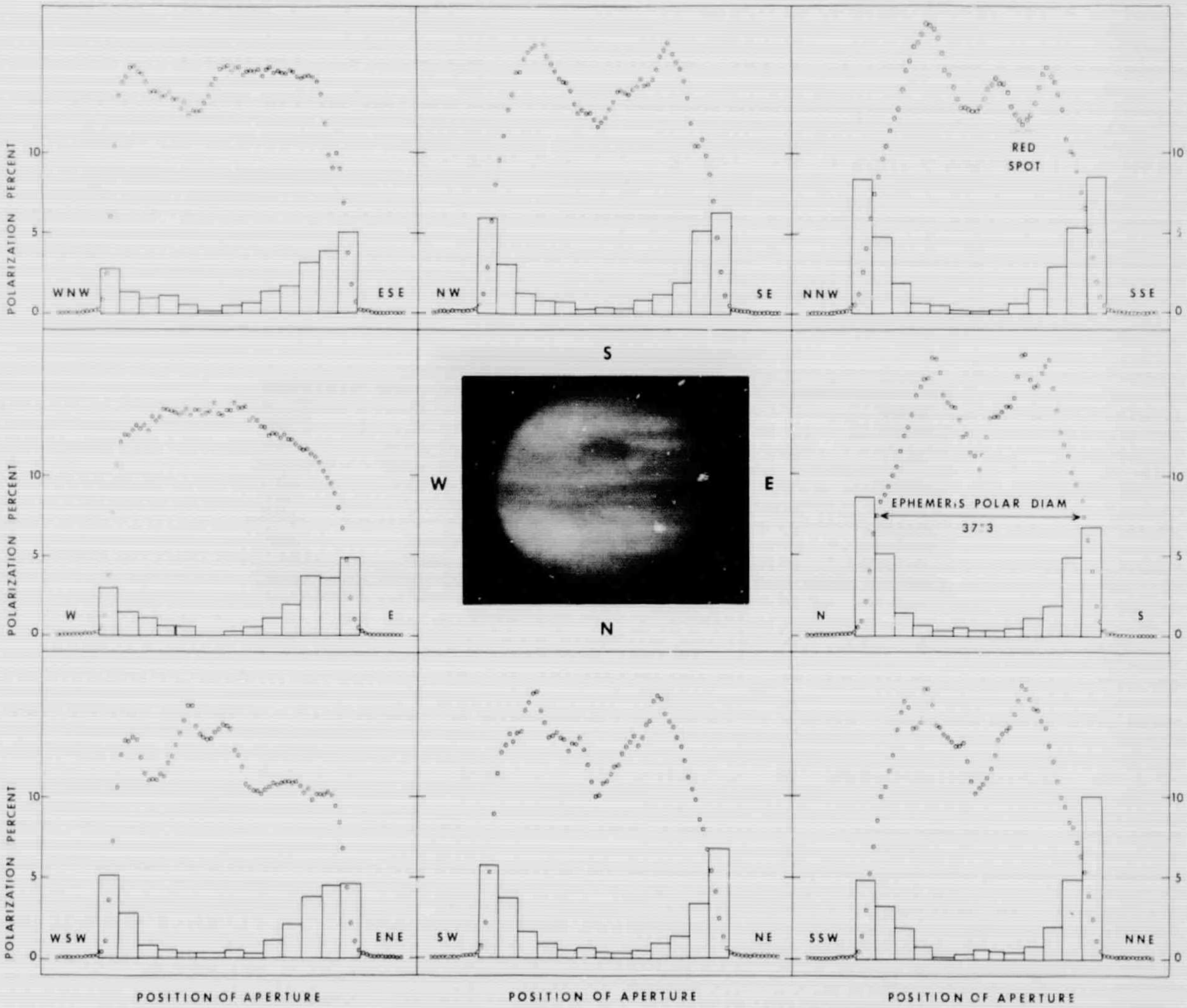

Figure 5. Intensity scans of Jupiter obtained on April 24 with UG 1 (λ3760). The histograms show relative polarization as averaged over 13 groups of consecutive elements along each scan. The photograph was obtained at New Mexico State University in blue light at the same time as the NNW-SSE scans were being made. The vectors which correspond to each point are shown in Figure 4. The ephemeris value of the N-S polar diameter, 37.3 arc seconds, falls at close to half the peak intensity of the light curve.

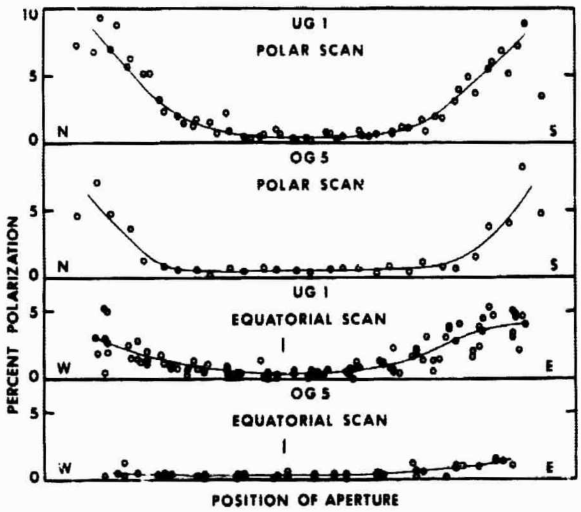

Figure 6. Degree of polarization of points on Jupiter's disk along polar and equatorial diameters. The polar scans in both colors show symmetry with respect to the center of the disk. The equatorial data for UG 1 are more nearly symmetrical with respect to the subsolar point (designated by vertical markers) than to the center of the planet. All observations are included.

regions. The NNW to SSE scan made on April 24 passed through the great red spot; the data do not indicate anomalous polarization for this area. Dollfus has obtained a similar result from measures in the visible regions.

A composite electric vector diagram of scans made with the UG 1 filter on ten nights, not including April 24, is shown in Figure 8. The average phase angle over the period was 8 degrees. In general, these data confirm those of Figure 5. Near the rim of the planetary disk the vector pattern indicates that the polarization is perpendicular to the edge of the disk.

Observations In The Yellow All observations made in the yellow (OG 5) are shown in Figure 9. In the polar regions and at the terminator and west limb, the directions of the vectors agree well with Lyot's results. As the polarization is very low near the center of the disk, the error in position angle is always large (20-30 degrees), and no definitive conclusions can be drawn. Much of the area of the planet was not explored by Lyot, and since he measured polarization in orthogonal planes directly related to the plane of vision and thus determined only whether the preponderant vibration was in one or the other plane, more precise comparisons are not possible.

Intensity scans in yellow light (OG 5) obtained at different position angles and apertures on four different nights at the Perkins telescope are shown in Figure 10.

CONCLUSIONS

Mars Whenever there was significant brightening at its south pole, the degree of polarization observed in the ultraviolet appeared to be less than that at middle latitudes. On one night clouds photographed on the east and west limbs showed more polarization in both spectral regions than that found at the center of the disk.

Jupiter The general polarization pattern found for this planet shows that the polarization is highly dependent upon the location of the area observed on the disk. It is not, as in the case of Mercury and Mars, mostly dependent upon phase angle and the position of the intensity equator.

The polarization of the great red spot and the dark bands measured in the ultraviolet did not show any appreciable differences from that found in adjacent areas.

The polarization in the ultraviolet is much stronger than it is in yellow and, except for measures made at the east and west limbs, the two patterns are similar at the periphery of the disk.

The vectors for the ultraviolet region begin to show a strong tendency to be perpendicular to the rim of Jupiter at about one-third the radius outward from the center of the disk and continue with increasing strength to its edge. However, in the yellow, at a distance of one-half the radius from the center, the position angles are more nearly parallel than perpendicular to the edge of the disk. More

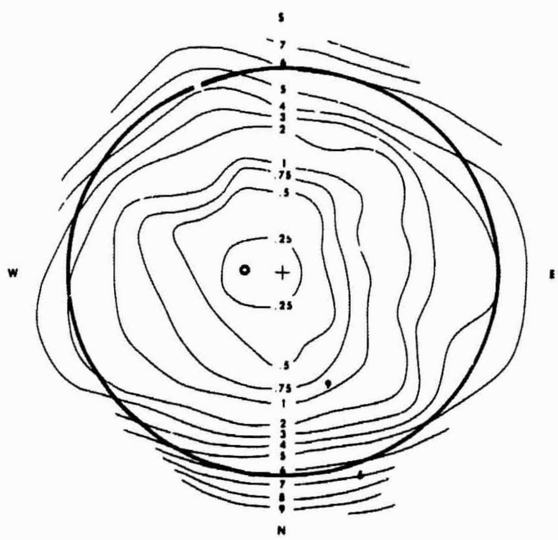

Figure 7. Lines of equal polarization over the disk of Jupiter obtained in the ultraviolet on April 24. These data suggest a symmetry with respect to the subsolar point, which is indicated by the circle.

extensive data must be secured before an accurate picture of the polarization pattern near the center of the disk can be obtained.

The symmetry of the degree of polarization with respect to the subsolar point and the direction of the vectors at the periphery of the disk indicate multiple scattering as the basic process in producing the observed results. This suggests that the polarization is produced by an optically dense atmosphere surrounding Jupiter. The same general explanation was first offered by Lyot (1929) and has been discussed by Ohman (1949) and H. C. van de Hulst (1948). The data show no evidence of scattering by particles oriented by magnetic fields.

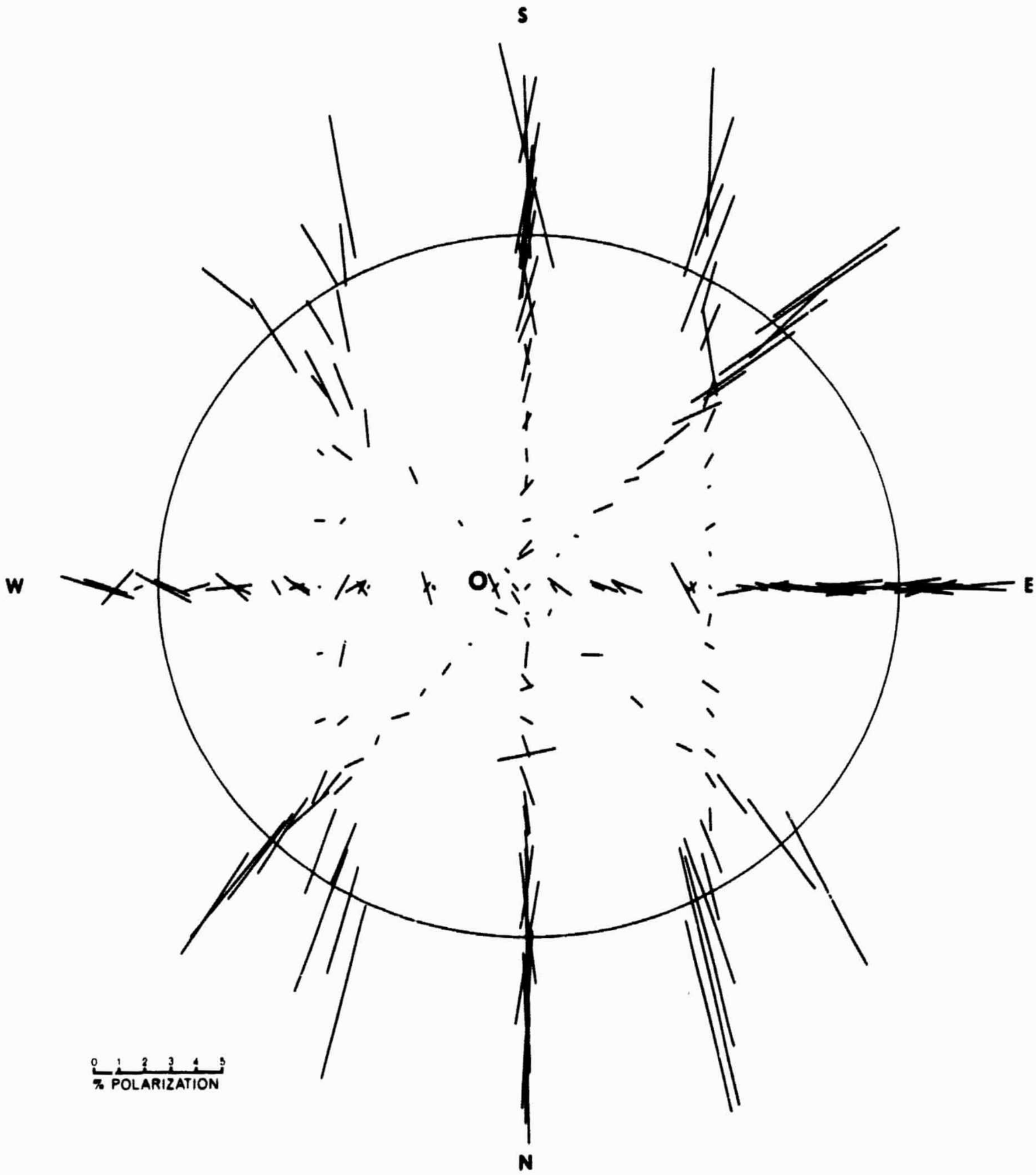

Figure 8. Observations similar to those described in Figure 4 but made on seven nights with the 72-inch and on three nights with the 30-inch reflector.

ACKNOWLEDGMENTS

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The planetary photographs obtained at the same time as the photoelectric observations have been most helpful with regard to data interpretation. The authors gratefully acknowledge the assistance rendered in this regard by observers of New Mexico State University Observatory and of the Planetary Research Center of the Lowell Observatory.

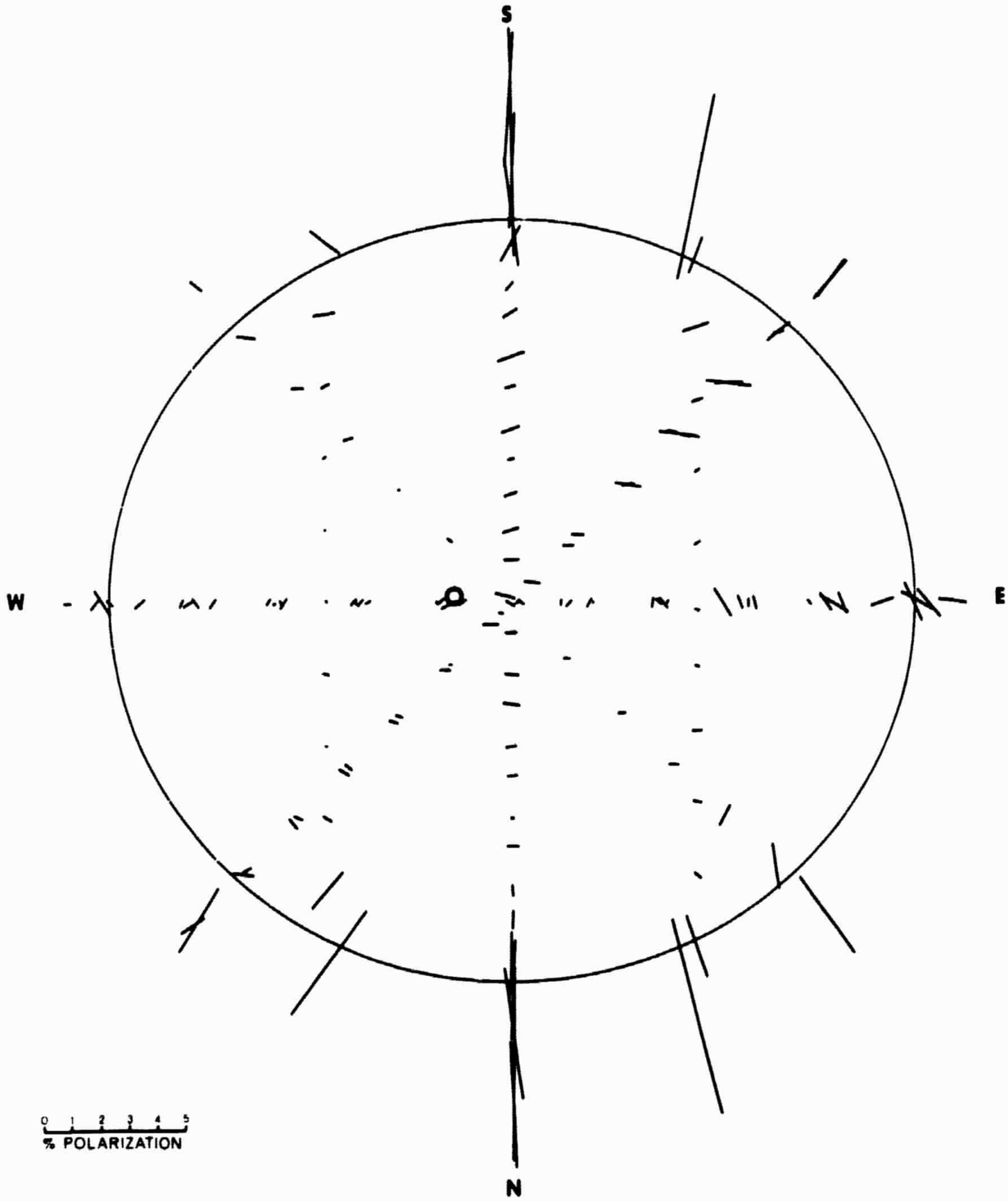

Figure 9. Polarization measures obtained in the visual at an effective wavelength of λ5740. The data are presented in the same form as Figures 4 and 8. Three of the equatorial scans were obtained at the 30-inch, the others at the Perkins telescope.

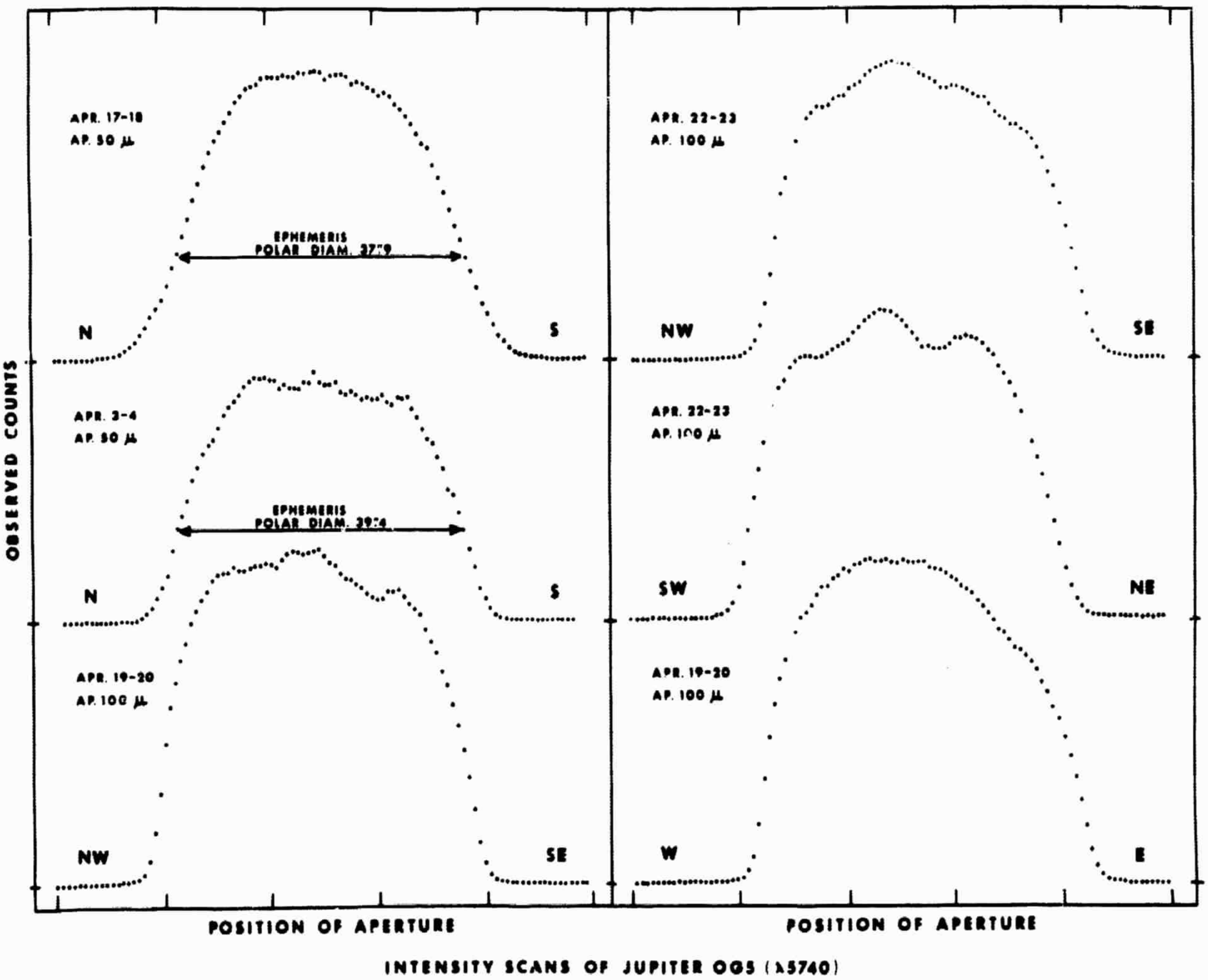

Figure 10. Intensity scans of Jupiter in yellow light. The two N-S scans show little evidence of the band structure.

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