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Final Report
"Polarization Studies of Uranus"
May 1, 1975 - June 15, 1976

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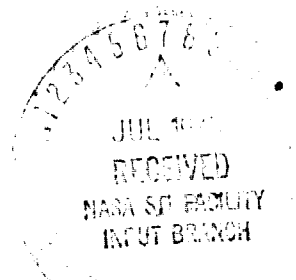
ABSTRACT

The whole-disk polarization of Uranus was measured over two apparitions in blue and red light. The behavior of the blue polarization as a function of phase angle is indicative of non-Rayleigh scattering. The red polarization phase curve, while not necessarily suggesting Rayleigh scattering, is at least consistent with that interpretation. One explanation of these data is that the blue radiation is scattered by the CH_4 haze layer suggested by others for Uranus while red radiation, because of methane absorptions above this layer, does not penetrate to or scatter significantly from this haze layer. There is no whole-disk circular polarization, as expected, confirming other observations and theoretical predictions.

In addition, polarization measurements of Comet West were carried out after perihelion. The results indicate that large particles are primarily responsible for the scattering of continuum light.

INTRODUCTION

Uranus is an attractive planet for scientific studies for a number of reasons. The mean density of Uranus implies an enrichment in the heavy elements intermediate between those of the terrestrial planets and those of Jupiter and Saturn which have a near-solar composition. This intermediate composition makes it important to studies of solar system evolution. Since mixing due to atmospheric circulation should ensure that the atmosphere reflects the envelope composition, atmospheric composition is an important test of solar system evolution theories (Cameron 1973). While constituents can be found spectroscopically, relative abundance determinations depend on atmospheric structure.

One reason atmospheric scientists are interested in Uranus is the stability of its atmosphere. This is a result of the weak heating of the planet due to its distance from the sun and the lack of an internal heat source. Fundamental theories of atmospheric circulation and structure in response to a weak external source can, therefore, be tested. Both of the above arguments for studying Uranus apply to Neptune; however, it is less amenable to study using ground-based techniques or spacecraft because of its smaller size and greater distance.

In an early paper on the atmospheric structure of Uranus, Belton, McElroy and Price (1971) indicated that measured equivalent widths of H_2 quadrupole lines were consistent with those calculated using a clear semi-infinite atmosphere. From the measured limb-darkening obtained from

Stratoscope II, Danielson, Tomasko and Savage (1972) proposed that a cloud deck beneath a finite clear layer was a better model for the atmosphere than either a clear semi-infinite layer or an atmosphere in which there are high clouds.

Two subsequent studies cast doubt on the hypothesis that the atmosphere was particle-free. Prinn and Lewis' (1973) analysis based on measured geometrical albedos and thermodynamics concluded that a high altitude haze of methane was present. Westphal (1972) reported limb brightening at 0.89 μ, the center of a strong methane band. Limb brightening can result from the presence of high albedo scatterers high in the atmosphere.

Belton and Price (1973) added support to the hypothesis that the atmosphere above the thick cloud deck was free of particles even though limb brightening was observed at 0.89 μ. They demonstrated theoretically that a vertically inhomogeneous atmosphere produced by pressure-induced opacity sources could result in limb-brightening at certain wavelengths.

It has not yet been clearly established just what the situation is for the atmosphere above the cloud deck on Uranus. It occurred to us that polarimetry could answer some questions about hazes and/or clouds. To illustrate, the whole disk linear polarization of Jupiter is negative (polarization vector parallel to the scattering plane) and it increases in magnitude as the phase angle increases (Lyot 1929). This cannot be explained by simple Rayleigh scattering processes since the resulting polarization would be positive (polarization vector perpendicular to the scattering plane). Therefore, the upper Jovian atmosphere must contain a

significant aerosol concentration. Saturn, on the other hand, has a whole disk polarization that is positive (Lyot 1929). This can be explained if there are fewer aerosols high in the atmosphere and molecular scattering dominates. Polarimetry should, also, be useful in interpreting conditions in the Uranian atmosphere.

We report here measurements of the linear polarization of Uranus taken during the period 1975 February - 1976 May. Two colors were used in an attempt to extract some vertical structure information from these data.

OBSERVATIONS

The use of polarization studies as a means of discriminating between models of the Uranian atmosphere has undoubtedly occurred to others; however, we found no measurements in the literature. The reason for this dearth of published data was apparent on our first attempt to measure the polarization. The observation indicated that any linear polarization for Uranus was less than 0.1% which is below the sensitivity of many polarimeters.

A successful measurement requires a careful determination of spurious linear polarization introduced by telescope and polarimeter. To reduce this systematic effect, we always used the symmetric Cassegrain focus. To determine the remaining small residual polarization for each telescope, we chose a set of unpolarized standard stars from Serkowski's list (1974). These stars were observed by Serkowski to have a typical residual polarization of $\lesssim$ 0.01%. By measuring stars whose residual polarizations are at different angles, one should be able to determine the spurious polarization to a level considerably below this.

Observations were made on four different telescopes with two polarimeters. It was found that measurements were consistent between telescopes, i.e., similar results were obtained at like phases. Stokes et al. (1974) and Stokes, Ekstrom and Swedlund (1976) describe the polarimeters used on the Cerro Tololo Inter-American Observatory 36-inch (91 cm), the McDonald Observatory 36-inch (91 cm) and 82-inch (208 cm),

and the Battelle Observatory 31-inch (79 cm) telescopes. The measurements were made using filters whose effective wavelengths and half-maximum transmission widths are 4500Å-1000Å, 6650Å-900Å and 6450Å-1200Å. Standard stars were generally observed on the same nights as Uranus. The Battelle Observatory data taken in 1976 were taken with the polarimeter positioned to measure only polarization perpendicular or parallel to the scattering plane. This procedure considerably decreases the error for a given integration time. The data appear in tables 1 and 2 and figures 1 and 2. Positive polarization denotes that the electric vector is perpendicular to the scattering plane and negative polarization is parallel to the scattering plane. In the figures no distinction is made between positive and negative phase angles, and we expect no difference. We are making the reasonable assumption that Uranus' small orientation change in a year's time does not significantly affect the polarization. The polarization from the two red filters are plotted together in figure 2. The errors quoted assume that the spurious polarization is completely determined to within the quoted errors. This may not be absolutely correct insofar as the residual polarization of the standards may not be zero, i.e., even though a number of standard stars were measured, their net polarization may be non-zero. Observations made at the same phase are presented as an average in the figures.

DISCUSSION

The blue polarization phase curve of figure 1 is considerably more structured than the red polarization phase curve of figure 2. Two features are immediately apparent. The polarization is positive beyond 2.0 degrees, and it is negative around 0.5 degrees. At opposition it approaches zero polarization, as expected for a homogeneous atmosphere. The trend in the data is to monotonically increase beyond 1.0 degree. The one point around 2° phase that interrupts this behavior is nevertheless statistically consistent with this increasing polarization.

Danielson, Tomasko and Savage (1972) find their limb-darkening data consistent with a Rayleigh scattering layer of optical depth 0.5 above an optically thick cloud deck. Since the Kodak 103a-G film used by Stratoscope II is sensitive to wavelengths short of 6000Å, we can assume that at the effective wavelength of our blue filter (4500Å) this layer has an optical depth of 0.5 or greater. The main finding then is that negative polarization is not consistent with a scatterer-free thick molecular layer above a cloud deck, i.e., some sort of haze or thin cloud layer is required rather high in the atmosphere. The red polarization phase curve does not show similar behavior. Generally, these data show no polarization save possibly at the largest phase angles obtainable. Red and near-infrared absorptions by methane prevent this radiation from penetrating to pressure levels in the atmosphere as great as those penetrated by blue radiation. It appears, therefore, that the blue radiation penetrates a haze layer, but red radiation does not.

COMET WEST

A few polarization measurements (three nights) of the continuum light from Comet West were obtained after perihelion. The four filters used each night give the same magnitude and angle for the polarization. Two possible sources for this wavelength independent linear polarization are electron scattering and scattering by very large dust grains. Both processes are possible in comets, but dust scattering produces most of the continuum light and, therefore, large dust grains should be responsible for the polarization.

ACKNOWLEDGEMENTS

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TABLE 1

RED WHOLE-DISK LINEAR POLARIZATION OBSERVATIONS (1975-1976)

Date	Filter	$10^4P/I$	Phase Angle	Polarimeter*	Telescope
21 Feb 75	6450	+0.1±1.4	-2°.67	B	BAT 31"
6 Mar 75	6450	+0.0±1.5	-2°.26	B	BAT 31"
11 Apr 75	6450	-1.0±1.3	-0°.56	B	BAT 31"
12 Apr 75	6450	+0.1±1.3	-0°.51	B	BAT 31"
9 May 75	6450	-1.1±1.6	+0°.97	B	BAT 31"
4 Feb 76	6650	+1.9±1.3	-3°.02	K	MC 36"
4 Mar 76	6650	+3.8±1.0	-2°.49	K	BAT 31"
23 Apr 76	6650	+1.8±1.4	-0°.14	K	BAT 31"
25 Apr 76	6650	+0.7±1.3	0°.00	K	BAT 31"

* "B" refers to polarimeter described in Stokes et al. (1974); "K" refers to polarimeter described in Stokes, Ekstrom and Swedlund (1976).

TABLE 2

BLUE WHOLE-DISK LINEAR POLARIZATION OBSERVATIONS (1975-1976)

Date	Filter	10^4P/I	Phase Angle	Polarimeter*	Telescope
6 Mar 75	4500	3.2±1.8	-2°26	B	BAT 31"
11 Apr 75	4500	-2.4±1.2	-0°56	B	BAT 31"
12 Apr 75	4500	-2.9±1.3	-0°51	B	BAT 31"
1 Jun 75	4500	-1.8±1.7	+2°06	B	BAT 31"
17 May 75[†]	4500	-0.6±2.1	+1°3′	K	CTIO 36"
1 Feb 76	4500	+5.1±1.0	-3°04	K	MC 36"
9 Feb 76	4500	+5.9±1.7	-2°99	K	MC 36"
10 Feb 76[†]	4500	+4.9±0.6	-2°97	K	MC 82"
3 Mar 76	4500	+3.4±1.0	-2°50	K	BAT 31"
7 Apr 76	4500	-0.3±0.9	-0°99	K	BAT 31"
21 Apr 76	4500	-6.5±2.7	-0°22	K	BAT 31"
23 Apr 76	4500	-1.4±1.2	-0°14	K	BAT 31"
25 Apr 76	4500	+0.4±1.2	0°00	K	BAT 31"
30 Apr 76	4500	+1.6±1.3	+0°21	K	BAT 31"
4 May 76	4500	-1.5±1.0	+0°48	K	BAT 31"
19 May 76	4500	-0.2±1.0	+1°27	K	BAT 31"
27 May 76	4500	+0.1±1.7	+1°66	K	BAT 31"

* "B" refers to polarimeter described in Stokes et al. (1974); "K" refers to polarimeter described in Stokes, Ekstrom and Swedlund (1976).

[†] No unpolarized stars were observed with these telescopes; however, the results are consistent with the other observations.
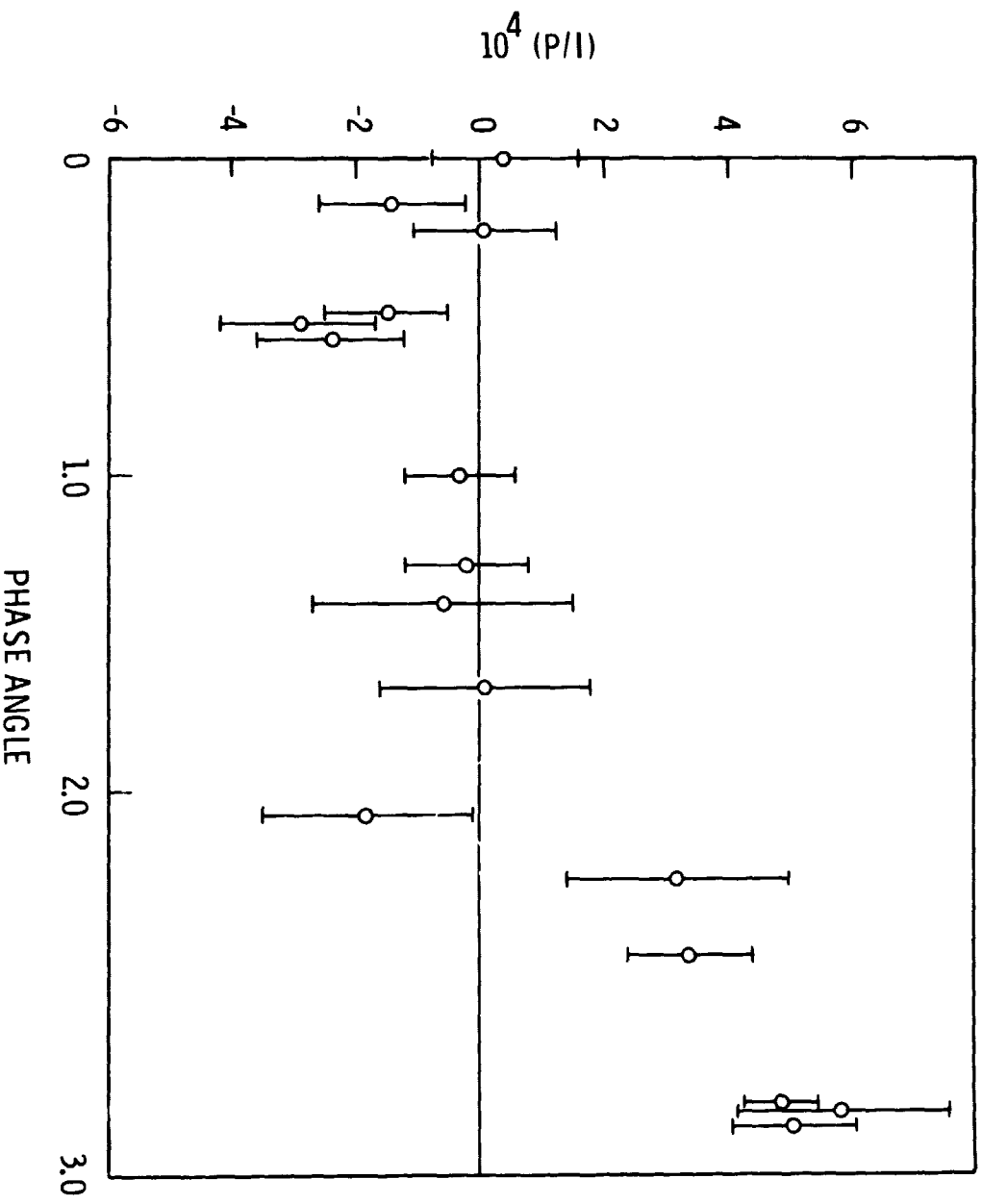
Fig. 1. WHOLE-DISK LINEAR POLARIZATION AS A FUNCTION OF PHASE ANGLE (BLUE).