THE ASTROPHYSICAL JOURNAL, **238**:935–940, 1980 June 15

SPECTROPOLARIMETRY OF OMICRON CETI AROUND THE 1978 MAXIMUM

LORENCE TOMASZEWSKI AND J. D. LANDSTREET
Department of Astronomy, University of Western Ontario

AND

IAN S. MCLEAN[1] AND GEORGE V. COYNE, S.J.
Lunar and Planetary Laboratory and Steward Observatory, University of Arizona
Received 1979 October 23; accepted 1979 December 13

ABSTRACT

The wavelength dependence of polarization of the prototype Mira variable *o* Ceti was observed around the time of the 1978 light maximum. Data were obtained at two phases with 20 Å resolution between 4000 and 6000 Å using the new University of Western Ontario IDS spectropolarimeter. Further observations were obtained using a University of Arizona filter polarimeter and the Royal Observatory Edinburgh scanning spectropolarimeter.

The data obtained show polarization generally rising from long wavelengths to shorter ones, with local decreases through the strongest TiO bands and excess polarized flux in Hγ and Hδ (which are in emission) and in Ca I λ4226 (which is in absorption). A strong drop in polarization is also found shortward of Hδ. These data are provisionally interpreted as resulting from the effects of scattering in an atmosphere which is not uniformly bright.

Subject headings: polarization — stars: individual — stars: long-period variables

I. INTRODUCTION

The intrinsic linear polarization of *o* Ceti (Mira) has been measured extensively in the past with broad-band filters ($\Delta\lambda > 500$ Å). Shawl (1975) overlaid in phase polarimetry from several cycles of its light curve and found that the polarization in the ultraviolet increases abruptly near phase 0.8 reaching a maximum value at phase 0.9. This rapid increase in polarization coincides closely in phase with the photometric eruption point (Fischer 1968, 1969) and the first appearance of the hydrogen emission lines. In general, the magnitude of the polarization increase is largest in the UV and decreases sharply from the blue to the yellow (Serkowski 1971). Also, at least in the early data, the position angle of the polarized light shows alternately high and low values (Serkowski 1971).

The first narrow-band multichannel spectropolarimetric observations of Mira were obtained by McLean and Coyne (1978, hereafter MC) near the 1977 maximum ($\phi = 0.97$). Those data, covering some 3000 Å at approximately 50 Å resolution clearly demonstrated the existence of a complex variation of polarization with wavelength. Features observed in the polarization spectrum included (1) a decrease in the amount of polarization p coincident with the strongest TiO bands, (2) a broad depression extending from 3450 Å–4250 Å but not associated with any obvious features in the flux spectrum, and (3) an increase in p at the hydrogen emission lines, indicating the presence of polarized Balmer-line flux. The position angle showed little variation with wavelength (less than 10°) but was at an unusually high (107°) value.

Most of the small number of red giant variables observed polarimetrically with sufficient resolution to detect small-scale polarimetric structure (Landstreet and Angel 1977; McLean and Clarke 1977; Coyne and Magalhães 1977, 1979; McLean 1979) show changes in p and/or θ at the strong molecular bands. Usually these stars also show a UV polarization depression, but the wavelength of the minimum and the width of the depression appear to be variable.

In this paper we present further spectropolarimetric observations of *o* Ceti at a resolution of 20 Å at two phases around the 1978 maximum. In addition, we have extensive narrow and broad-band observations taken over a longer period around maximum. These observations reveal dramatic changes in the wavelength dependence of the polarization during the rise to maximum and confirm the presence of the polarized Balmer-line emission. In addition, we have observed a peak in the polarization data associated with the Ca I λ4226 resonance line.

In § II we briefly describe the various polarimeters which have been used in this study. The individual observations are presented in detail in § III. In the final section (§ IV), we discuss the changes between the 1977 and 1978 maxima and suggest possible physical mechanisms that could contribute to these changes.

[1] Now at the Royal Observatory, Edinburgh, Scotland.

II. INSTRUMENTATION

Observations were made independently at the University of Western Ontario (UWO) and the University of Arizona (UA).

All observations at UWO were made with the 1.22 m telescope and IDS spectropolarimeter. Since this instrument has not been previously described in the literature, we present a brief outline of its operation. A more detailed description will be published elsewhere (Tomaszewski, Symonds, and Landstreet 1980). The detector is an intensifier-dissector scanner (IDS) which consists of an ITT three-stage image intensifier immersion oil coupled to an ITT image dissector. The dissector aperture is 37 μm × 250 μm. This system operates on the same principle as the Lick IDS (Robinson and Wampler 1972) except that we use only a single 513 channel sweep, about 2 cm long. Data collection hardware has been designed around the use of multiplexed presettable counters and static MOS shift registers. The detector has been mounted on the observatory's Boller and Chivens Casegrain spectrograph. The original camera has been replaced by an Aero-Ektar lens, which in conjunction with a 300 lines mm^{-1} grating produces a first-order linear reciprocal dispersion of approximately 100 Å mm^{-1}. Each channel covers 4 Å for a total sweep length of slightly over 2000 Å. Typically the instrumental resolution of our IDS is four channels, or approximately 16 Å. However, to improve the signal-to-noise ratio, the UWO data in this paper have been averaged in 20 Å bins. Polarizing optics are mounted in a spacer cavity ahead of the spectrograph entrance slit and consist of (*a*) a calibration Polaroid (Polaroid Corporation HNP′B), (*b*) a rotatable achromatic quarter-wave plate, (*c*) a Pockels cell modulator, and (*d*) a Polaroid analyzer (HNP′B); operation of the polarization modulator is similar to the arrangement used by Landstreet and Angel (1975). To minimize the cross-talk between signals recorded for the two modulator states which is produced by the slow decay of the image tube phosphor, the Pockels cell is switched at a frequency of one hertz. The modulation efficiency of the system was determined separately for each observing run by fitting the Serkowski empirical curve (Serkowski, Mathewson, and Ford 1975) to observations of the interstellar standards 9 Gem and HD 14433. We calibrated the modulation efficiency on stellar polarization standards rather than with the calibration Polaroid because of a serious blue leak in the HNP′B calibration Polaroid. Observations of these interstellar standards also defined the zero of the position angle in the standard equatorial system. Standard errors were determined from the photon counts and corrected for additional instrumental noise in the IDS. The correction factor was determined from polarization observations of unpolarized and unmodulated sources.

During 1977 the main instrument used at UA was the Digicon spectropolarimeter, in which photoelectrons emitted by an S-11 photocathode form an image on an array of 106 silicon diodes. Magnetic stepping over half-diode intervals gives effectively 214 channels. A rotating superachromatic half-wave plate and a fixed Glan prism in front of the spectrometer were used for measuring polarization simultaneously in all channels. The data discussed here were secured in a low-resolution mode ($\sim$32 Å per diode) using a transmission grating prism (grism). Averages over three channels (1.5 diodes) were generally computed except in a few cases. Other results obtained at higher resolution near the 1977 light maximum were reported earlier (McLean and Coyne 1978) and calibration procedures and further details of the instrument are given in McLean *et al.* (1979). The Digicon detector became nonoperational in 1978 because of a decrease in sensitivity and is currently being replaced with an intensified charge injection device (ICID) detector.

The 1978 UA observations of Mira were obtained using either filter polarimetry or a single-channel grating spectropolarimeter. The Minipol polarimeter has been described by Frecker and Serkowski (1976). Wide-band filters with the following designations and effective wavelengths (μm) for a 2500 K blackbody were used: U(0.37), B(0.46), G(0.51), O(0.65), R_1(0.70), I_1(0.80), R_2(0.88), I_2(0.97).

Through a collaborative program with Dr. R. D. Wolstencroft at the Royal Observatory Edinburgh (ROE), Scotland, a single-channel, wavelength-scanning spectropolarimeter was made available to us for the 1978 maximum of Mira. A photoelastic modulator followed by a Polaroid analyzer comprises the basic polarimeter. Linear polarization measurements require the use of suitably oriented quarter-wave plates in front of the modulator. Spectral resolution is obtained with a commercial McPherson grating monochromator. For these studies, the exit slit was set to give a resolution of 50 Å. Spectrum scanning and/or polarimetry (at preset wavelengths) could be performed under computer control.

In all of the above polarimeters, instrumental polarization effects were found to be negligible for the present study.

III. OBSERVED POLARIZATION CHANGES IN MIRA

The polarization data obtained around the 1978 maximum are displayed in Figure 1. At the top of the figure we show a representative flux spectrum near maximum light. This spectrum is not corrected for

FIG. 1.—The wavelength dependence of polarization (p) and position angle (θ) of *o* Ceti for 1978. The top section is a composite flux spectrum from IDS (resolution = 20 Å) and ROE (30 Å) data. The positions of the strongest spectral features are indicated by broken vertical lines. The remaining sections are divided into three panels according to phase. Panel 1 contains broad-band (U, B, G, O, R_1, R_2, I_1, I_2) and ROE (50 Å) observations for phases 0.70, 0.80, 0.88. Panel 2 presents p and θ for phases 0.92 (IDS; 20 Å) and 0.94 (ROE; 50 Å). The last panel contains IDS (20 Å) data for phase 1.09. The error bars are $\pm 1\ \sigma$.

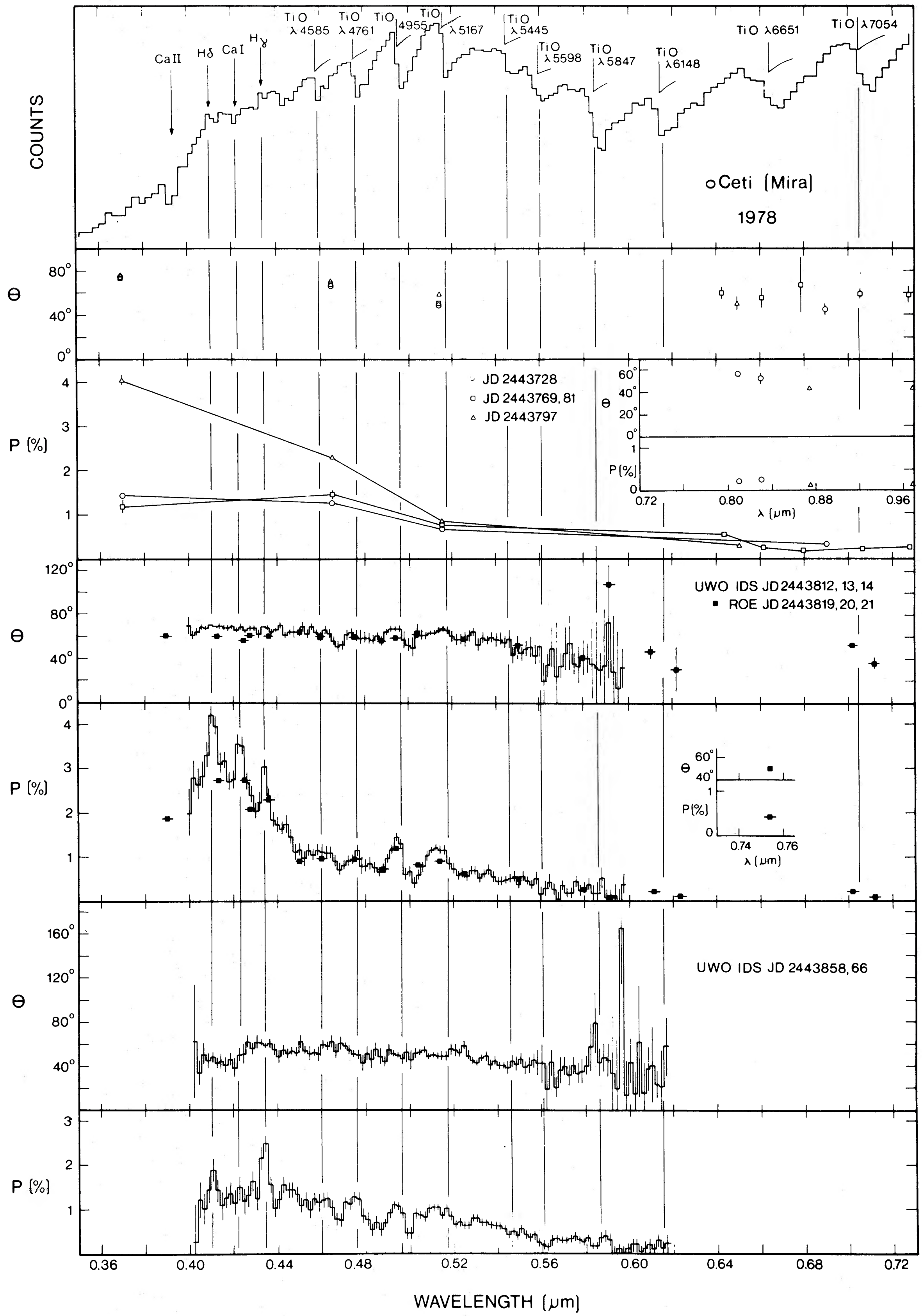
CaII
Hδ
CaI
Hγ
TiO λ4585
TiO λ4761
TiO 4955
TiO λ5167
TiO λ5445
TiO λ5598
TiO λ5847
TiO λ6148
TiO λ6651
TiO λ7054
COUNTS
o Ceti (Mira)
1978
Θ
80°
40°
0°
P (%)
JD 2443728
JD 2443769, 81
JD 2443797
λ (μm)
UWO IDS JD 2443812, 13, 14
ROE JD 2443819, 20, 21
120°
160°
UWO IDS JD 2443858, 66
0.36
0.40
0.44
0.48
0.52
0.56
0.60
0.64
0.68
0.72
WAVELENGTH (μm)

FIG. 1

instrumental response but simply shows relative count rates at various wavelengths. Between 4000 and 6200 Å the spectrum is based on UWO IDS data with 20 Å resolution; outside this range we used an ROE scan with 30 Å resolution. This spectrum clearly shows numerous TiO absorption bands, the Hγ and Hδ Balmer lines in emission and Ca I λ4226 absorption.

Below the flux spectrum, the data are grouped in three panels by phase. Broad-band polarization observations which were obtained with Minipol on JD 2,443,728 ($\phi \approx 0.70$), 2,443,769 − 81 ($\phi \approx 0.80$), and 2,443,797 ($\phi \approx 0.88$) are shown in the upper panel. (Phases are calculated relative to maximum light, which according to AAVSO data occurred—about 20 days late—around JD 2,443,838. We use the average period = 331.65 days.) Although the first two data sets were obtained several weeks apart, they are very similar and show a preeruption polarization rising with decreasing wavelength to about 4500 Å and then apparently leveling off.

The third set of broad-band data was obtained between the photometric eruption point JD 2,443,790 ($\phi \approx 0.85$) and maximum light. This is also true of the data in the next panel. Observations from JD 2,443,812 − 14 ($\phi \approx 0.92$) are IDS data with 20 Å resolution and the data from JD 2,443,819 − 21 ($\phi \approx 0.94$) were obtained with the ROE spectropolarimeter with 50 Å resolution. The continuum polarization now increases to shorter wavelengths, plateaus around 4100 Å, then falls off in the UV. Sharp drops in the polarization occur through the TiO bands at λλ4955 and 5167 and to a lesser extent through the band at λ4761. Narrow peaks occur in p at the Balmer Hγ and Hδ lines, similar to those seen by MC at the 1977 maximum. Hβ is not detected either in the flux or the polarization spectra. A third narrow peak in p occurs at the wavelength of the Ca I λ4226 line. This peak is very clear in the IDS data and may also be seen in the ROE data.

In the lowest panel we show a final scan of Mira obtained nearly a month after maximum on JD 2,443,858 − 66 ($\phi \approx 1.09$) with the IDS. Longward of 4450 Å, the scan is essentially identical to the earlier IDS scan. However, the broad polarization peak between 4250 and 4000 Å has almost disappeared, and the sharp peaks at Hδ and Ca I λ4226 are likewise almost entirely gone. The peak at Hγ lies outside the 4000–4250 Å hump and although reduced in strength is still quite visible.

Position angle variations are rather small, both in time and in wavelength. The position angle spectrum for JD 2,443,812 − 14 shows a slight rotation of about 20° from the blue to red ends and still smaller variation across some TiO bands. No significant position angle changes occur at the p spikes coinciding with Hγ, Hδ, and λ4226. In the later IDS scan the position angle spectrum has almost the same form as seen in the earlier scan, except that shortward of 4250 Å the position angle varies somewhat more with wavelength and tends to be about 10° smaller than in the earlier scan.

The Ca I polarization peak was also found in a previously unpublished Digicon scan obtained a month before the 1977 maximum on JD 2,443,447 ($\phi = 0.90$). This scan is shown in Figure 2, together with the scan published by MC from JD 2,443,473 ($\phi = 0.97$). The earlier scan clearly shows the λ4226 feature, but no evidence of it is seen in the scan one month later.

Note that the position angle of polarization is about 45° smaller during the 1978 maximum than during the 1977 one.

IV. DISCUSSION

We consider the extent to which the data may be understood on the basis of the model proposed by Harrington (1969, 1970). In this model, the radiation emitted into the line of sight from near the stellar limb is polarized by Rayleigh scattering mainly from H_2. Net polarization of the stellar flux results from a nonuniform brightness distribution over the stellar

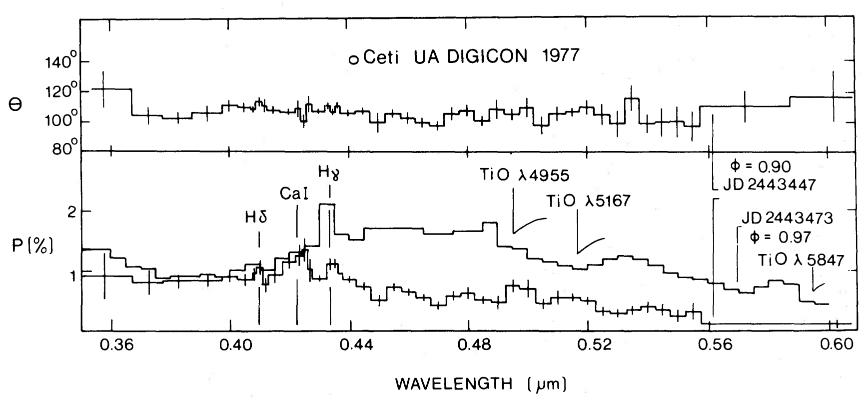

FIG. 2.—Digicon spectropolarimetry of *o* Ceti for 1977. Polarization and position angle data with ±1 σ error bars have been plotted for phase 0.90. Only the polarization data (50 Å) for phase 0.97 (McLean and Coyne 1978) have been plotted, and the error bars have been omitted for clarity.

photosphere, due perhaps to large convection cells (Schwarzschild 1975) or to nonspherical pulsation (Shawl 1974).

Suppose, to be definite, that there is one large spot region near the limb which is somewhat hotter and brighter than the rest of the photosphere. Radiation from this region, like that from other parts of the limb, is polarized by scattering. The excess brightness of the spot breaks the azimuthal symmetry and results in residual net polarization. We expect this polarization to rise fairly rapidly toward shorter wavelengths both because the ratio of scattering to absorption increases (because of the increased scattering cross section which goes as λ^{-4}) and because the fraction of the total flux coming from the spot increases toward shorter wavelengths because of its higher temperature.

In strong absorption bands which are produced more or less uniformly over the star, we expect the polarization to drop. At wavelengths where absorption is strong, photons are likely to have last interacted with photospheric material by absorption and reemission (which usually results in no polarization) rather than by scattering. Thus since local emission is largely unpolarized, the integrated radiation will be as well. This is essentially what is observed. The polarization rises to its largest local values at wavelengths where TiO absorption is weakest, shortward of band heads at $\lambda\lambda$4761, 4955, and 5167. Where the molecular absorption is stronger, the polarization drops to lower values. As expected, the general level of polarization rises to shorter wavelengths.

To account for the increase in polarization through the Balmer lines at constant position angle, we must have Balmer-line photons scattered with the same asymmetry as continuum radiation, but with the asymmetry enhanced. This could be achieved by having the Balmer emission arise near $\tau_\nu \approx 1$, so that Balmer photons are likely to be scattered as they emerge. The asymmetry required implies that the Balmer line emission is strongest in our bright spot and that the ratio of Balmer-line flux from the spot to that from other parts of the limb is greater than the ratio of continuum flux from the spot to that from the rest of the star. In fact, the Balmer-line emission might even arise *only* in the spot.

Excess polarization (at constant θ) through the Ca I λ4226 line might be produced in two ways. The polarization could be due to Ca I emission in the spot, occurring in the same region as the Balmer-line emission. Since λ4226 appears strongly in absorption over the rest of the photosphere, the integrated line could appear in absorption while containing significant excess scattered and polarized emission flux from the spot. Alternatively, the excess polarization could be due to the fact that λ4226 is a resonance line of Ca I, so radiative transfer in the line will mainly occur through scattering rather than absorption and thermal reemission. If the strength of the λ4226 line were constant over the photosphere, the polarization would probably decrease through the line even though the ratio of scattering to total extinction is higher in the line than in the nearby continuum. (This would occur because for large values of $h\nu/kT$ the strong source-function gradient can only enhance local polarization when an appreciable fraction of the scattered flux is thermal rather than scattered in origin, as pointed out by Harrington 1969, 1970.) To increase the polarization in the residual flux in the λ4226 line if it is only present in absorption, we must have the line weaker in the spot than it is in the rest of the photosphere. Because of the low ionization potential of Ca I, the higher excitation level in our hypothetical spot might well produce this effect. The time dependence of the polarization effects in the Balmer lines and in the Ca I line is probably due to a combination of (1) rising emitting layer (reduced scattering), (2) spreading of spot (reduced asymmetry), and (3) weakening excitation.

On this picture, the strong dip in polarization shortward of Hδ is probably due to the effects of numerous strong absorption lines around 4000 Å. Changes of position angle from cycle to cycle might be understood in terms of changes in the spot location.

It thus appears reasonable to hope that the observed polarization data may be understood as arising simply from the effects of transfer in an atmosphere which is not uniformly bright. This hypothesis, of course, needs to be tested by more detailed modeling. It is clear that if this model is correct, the data presented in this paper potentially contain a large amount of information about the geometrical distribution of brightness and emission over the stellar photosphere.

This work was supported by the National Science and Engineering Research Council of Canada and the National Science Foundation. We acknowledge the assistance of M. Rasche in the preparation of the figures and E. Goodall in the typing of the manuscript. The UWO IDS spectropolarimeter owes its existence to the skilful efforts of G. Symonds, M. Debruyne, W. Stewart, and J. Conville.

REFERENCES

Coyne, G. V., and Magalhães, A. M. 1977, *A.J.*, **82**, 908.
———. 1979, *A.J.*, **84**, 1200.
Fischer, P. L. 1968, *Non-Periodic Phenomena in Variable Stars*, ed. L. Detre (Academic: London).
———. 1969, *Ann. Univ. Sternwarte Wien*, **28**, No. 4, 138.
Frecker, J. E., and Serkowski, K. 1976, *Appl. Optics*, **15**, 605.
Harrington, J. P. 1969, *Ap. Letters*, **3**, 165.
———. 1970, *Ap. Space Sci.*, **8**, 227.
Landstreet, J. D., and Angel, J. R. P. 1975, *Ap. J.*, **196**, 819.
———. 1977, *Ap. J.*, **211**, 825.
McLean, I. S. 1979, *M.N.R.A.S.*, **186**, 21.
McLean, I. S., and Clarke, D. 1977, *M.N.R.A.S.*, **179**, 293.
McClean, I. S., and Coyne, G. V. 1978, *Ap. J.* (*Letters*), **226**, L145 (MC).
McLean, I. S., Coyne, G. V., Frecker, J. E., and Serkowski, K. 1979, *Ap. J.*, **228**, 802.

Robinson, L. R., and Wampler, E. J. 1972, *Pub. A.S.P.*, **84**, 161.
Schwarzschild, M. 1975, *Ap. J.*, **195**, 137.
Serkowski, K. 1971, *Kitt Peak Obs. Contrib.*, No. 554, 107.
Serkowski, K., Mathewson, D. S., and Ford, V. L. 1975, *Ap. J.*, **196**, 261.
Shawl, S. J. 1974, *Pub. A.S.P.*, **86**, 843.
———. 1975, *A.J.*, **80**, 602.
Tomaszewski, L. A., Symonds, G., and Landstreet, J. D. 1980, in preparation.

George V. Coyne and Ian S. McLean: Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721

J. D. Landstreet and Lorence Tomaszewski: Department of Astronomy, University of Western Ontario, London, Ontario N6A 5B9, Canada