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DETECTION OF POLARIZATION VARIATION ACROSS ABSORPTION FEATURES OF MIRA VARIABLES

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ABSTRACT

The wavelength dependence of polarization has been measured in five Mira variables and one RV Tauri star over the range 3300–11000 Å, with resolution between 20 and 160 Å. All the Mira variables observed show significant changes in polarization across some molecular or atomic absorption features, indicating that at least part of the polarization of these stars arises in the stellar atmosphere rather than in a circumstellar dust shell.

Subject headings: polarization — stars: atmospheres — stars: circumstellar shells — stars: long-period variables

I. INTRODUCTION

Many variable cool giants exhibit intrinsic linear polarization. Both percentage polarization and position angle characteristically vary with time, not necessarily in phase with light variations. The polarization is usually largest in the ultraviolet. Variations in position angle with wavelength are common. The time and wavelength dependence of polarization in broad bands ($\Delta\lambda \geqslant 10^3$ Å) has been studied by numerous authors (Shakhovskoj 1963; Serkowski 1966, 1970; Zappala 1967; Dyck 1968; Kruszewski, Gehrels, and Serkowski 1968; Dombrovskii 1970; Dyck and Sandford 1971; Shawl 1975).

It seems quite likely that in at least some cases the polarization originates by scattering from an asymmetric cloud of circumstellar grains. Several lines of evidence point to this conclusion. (1) A substantial infrared excess is found for many cool variables, probably due to a circumstellar cloud of heated grains (Woolf and Ney 1969). (2) Dyck *et al.* (1971) have shown that average visual polarization in a wide sample of cool giants and supergiants is correlated with excess flux at 11 μm. (3) Small grains acting as Rayleigh scatterers can lead naturally to the strong rise of polarization into the ultraviolet that is often observed (Kruszewski, Gehrels, and Serkowski 1968; Zellner and Serkowski 1972). (4) In highly obscured M stars, circular polarization is quite common, probably due to multiple scattering in optically thick circumstellar dust with skew geometry (Gehrels 1972; Serkowski 1973; Angel and Martin 1973). However, evidence that the relationship between dust envelopes and polarization may not be as direct as has been supposed has recently been presented by Forrest, Gillett, and Stein (1975), who find no time variation of infrared flux in stars in which the polarization varies greatly.

Another location in which polarization can arise is the stellar atmosphere. Chandrasekhar (1960) first showed that the polarization in an electron-scattering atmosphere reaches 11% at the limb. This is because the final scatterers are illuminated preferentially from below. Harrington (1969) extended this argument to Mira atmospheres, where there is Rayleigh scattering by H_2. He showed that the effect of absorption in the visible, where the gradient of the source function is very great, is to produce radiation even more strongly directed from the center of the star and hence more polarization than in the electron-scattering case. Harrington argues that sufficient asymmetry to account for the observed polarization could be caused by large-scale temperature variations over the surface of only 100° in 2000°, or alternatively by nonradial pulsations. In either case, the critical test for polarization produced in this way is that it will change across absorption bands, while no variation in polarization across bands is expected for polarization produced by circumstellar grains.

This prediction has never been adequately tested, although Dyck and Sandford (1971) have argued that atmospheric polarization is not present because similar wavelength dependence of polarization is observed in early and late M stars, while the TiO strength increases greatly with later spectral type. In this paper we present the results of observations of the wavelength dependence of six late-type variable stars, obtained with sufficiently high resolution and accuracy to detect polarization variations across strong absorption features. These observations cover the spectral range 3300–11000 Å, mostly with a resolution of 160 Å shortward of 5800 Å and 40 Å longward of that wavelength. All but one of the stars were observed only

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once each; rough spectrophotometry, usually having the same resolution as the polarimetry, was obtained for each star at the same time as the polarization spectrum. In the next section of this paper, we discuss the technique of observation and the main features of the data; in the final section we shall explore some conclusions that may be drawn from the new observational material.

II. OBSERVATIONS

The observations presented in this paper were obtained with the multichannel spectrophotometer (MCSP) on the 5 m telescope at Mount Palomar Observatory (Oke 1969). The MCSP was converted into a polarimeter by the addition of a Pockels cell modulator above the entrance aperture, as described by Angel and Landstreet (1974). Linear polarization measurements were made with this modulator by the addition of a Fresnel rhomb, which acts as an achromatic quarter-wave plate, above the modulator. Observations were made with the rhomb set at either two or four successive positions 45° apart. All observations were corrected for the effects of night-sky background and instrumental efficiency. Standard errors were computed from counting statistics. Observations of unpolarized stars and of stars having known interstellar polarization gave results in good agreement with previous broad-band measurements, confirming that the system was operating properly.

The polarimetric measurements were made while the Moon was up, sometimes on nights of poor photometric quality. To reduce the amount of (possibly variable) polarized night sky as much as possible, the MCSP aperture used was generally just a little larger than the stellar seeing disk. Under these circumstances, accurate spectrophotometry is not possible. In spite of this, the importance of obtaining simultaneous polarimetry and spectrophotometry led us to try to extract some spectrophotometric information from the count rates recorded during the polarization measurements, for comparison with the polarization spectra. For calibration purposes, one "standard" star was observed during each observing run and used, together with observations of a tungsten lamp (which was used for smoothing), to calibrate the sensitivity of the MCSP system. Correction for atmospheric extinction was made using the mean extinction coefficients for Mount Palomar given by Hayes and Latham (1975). For observations made during 1973 June, the photometric standard star θ Vir (Oke 1964) was used. For later runs, we observed A0 V stars of normal colors and high galactic latitude (HD 23258 in 1974 September and HD 75469 in 1975 April) and assumed that each has an energy distribution identical to that of Vega as given by Hayes and Latham (1975), except for a shift equal to the V-magnitude of the star. The use of stars which do not have measured narrow-band spectrophotometry as standards introduces an uncertainty of perhaps 0.1 mag into the calibration, while the poor quality of some of the nights and the small apertures used lead to a scatter of up to 0.2 mag (but usually less than 0.1 mag) in the observed count rates from run to run; we estimate that some of our absolute spectrophotometry may be in error by as much as a quarter of a magnitude. However, the spectrophotometry usually appears to have a noise level of less than about 0.1 mag over regions a few hundred Å wide, and our flux spectra show quite clearly the molecular bands and even some of the strongest atomic lines present in the stars observed, with sufficient accuracy to permit useful comparison of the flux and polarimetric spectra of the stars observed.

The stars observed were chosen from among the brightest red variables which have been found by other observers to have large intrinsic polarization. All the Mira variables are at high galactic latitudes and are presumed to show little interstellar polarization. All but R Lep were observed near maximum light, mainly to give as much accuracy as possible in the polarimetry. Several other red variables were also observed briefly

TABLE 1

RED VARIABLE STARS OBSERVED FOR POLARIZATION

Star (1)	HD No. Spectral Type (2)	Variability Period (3)	Date ϕ (4)	$\Delta\lambda_R$ $\delta\lambda_R$ (5)	$\Delta\lambda_B$ $\delta\lambda_B$ (6)	Photometric Quality (7)
R And...........	1967	M	1973 Jun. 22	40	160	C
	S6, 6e	409	0.94	40	20	
			1974 Sep. 6	40	160	B
			0.96	20	10	
R Lep...........	31996	M	1974 Sep. 9	40	160	A
	N6e(C7_6e)	432	0.49	40	20	
R Boo...........	128609	M	1973 Jun. 20, 22	40	80	C
	gM3e–M5e	223	0.02	40	20	
RU Her..........	145459	M	1975 May 1	40	160	A
	M7e	485	0.07	20	10	
U Her...........	148206	M	1975 Apr. 29	20	160*	A
	gM6.5e–M8e	406	0.97	20	10	
R Sct...........	173819	RV	1973 Jun. 20	40	20	B
	G0e–K0p	133	0.46†	40	20	

* Spectrophotometry with $\Delta\lambda_R = \Delta\lambda_B = 20$ Å.

† Counted from deep minimum (Serkowski 1970).

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but were found to have polarization of well under 1% at the time of observation; they were not investigated completely.

Details of the polarimetric observations are given in Table 1. The contents of successive columns are as follows: (1) The star name; (2) the HD number and spectral type; (3) the type of variability (M, Mira; RV, RV Tauri) and period in days; (4) the date of observation and phase as evaluated from AAVSO light curves kindly supplied by Mrs. J. A. Mattei; (5) and (6) the wavelength resolution $\Delta\lambda$ and spacing $\delta\lambda$ of individual data points (in angstroms), with the values for $\lambda > 5460$ Å (the red data), given in column (5) followed in column (6) by the values for $\lambda < 5810$ Å (the blue data; the region of the spectrum between 5460 and 5810 Å is observed in both first and second order of the grating); and (7) an estimate of the photometric quality of the night (A, excellent to C, mediocre). The measured flux and polarimetric spectra are displayed in Figures 1 through 7. The spectrophotometry is shown at the bottom of each figure, with $m_{1/\lambda} = -2.5 \log f_\nu - 48.6$ as ordinate. In the middle the percentage polarization $p = (p_x^2 + p_y^2 - \sigma_p^2)^{1/2}$ is plotted, where p_x and p_y are the measured polarization components at equatorial position angles 0° and 45°, and $\sigma_p = (\sigma_x + \sigma_y)/2$ is the average standard error of a single polarization component. (In general, observations were made in such a way that $\sigma_x \approx \sigma_y$.) At the top of each figure is the equatorial position angle $\theta = \frac{1}{2} \tan^{-1} (p_y/p_x)$. Representative error bars of $\pm 1\ \sigma_p$ are plotted at intervals above p, and above θ appear error bars of $\pm 1\ \sigma_\theta$, where $\sigma_\theta = 28^\circ\!.65\ \sigma_p/p$ for $p \geq \sigma_p$, otherwise $\sigma_\theta = 51^\circ\!.96$. Where the red and blue data overlap, the blue data are always plotted because of their higher signal-to-noise ratio; for some stars, the red data are shown in the background. The low count rates in the ultraviolet and infrared lead to a very low signal-to-noise ratio for individual data points, making it difficult to see trends in the data. To reduce the noise and bring out major features of the data, running means of nine points are plotted for $\lambda <$ 4000 Å and $\lambda > 10850$ Å. (This smoothing of blue data is extended to 4500 Å for the 1973 observations of R And, and to 5700 Å for R Lep.) The improved signal-to-noise ratio is reflected in reduced error bars and smaller point-to-point scatter. It should be noted that, because of the large ratio of resolution in the blue (usually 160 Å) to spacing (usually 10 or 20 Å), this procedure degrades the ultraviolet spectral resolution only slightly to $\Delta\lambda_B \lesssim 250$ Å, while reducing fluctuations by about a factor of 3.

The prominent absorption lines and bands in the flux spectra are identified as far as possible. Where features are seen in the polarization spectra that appear to correspond to features in the flux spectra, vertical lines aid the eye in matching the spectra. The low resolution of the blue polarimetry is generally reflected in the blue spectrophotometry. However, a photometric scan was obtained with $\Delta\lambda_B = \Delta\lambda_R = 20$ Å for U Her, so that, in the blue flux spectrum of this star, far more detail is visible than in the other spectra.

All the polarization spectra presented here show significant structure on a scale of a few hundred angstroms or less, with the exception of the RV Tauri star R Sct, whose spectrum is fairly smooth. The major features of the individual spectra are as follows.

R Bootis, RU Herculis, U Herculis.—The flux spectra of these three M-type Mira stars are all quite similar. The absorption features are primarily molecular bands of TiO which are somewhat weaker in R Boo than in the other two stars because of its earlier spectral type. In the blue region of the polarization spectrum, all three stars show broad maxima of percentage polarization (at about 3600, 4300, and 5000 Å in RU Her and U Her, and 3600 and 4400 Å in R Boo) that have no obvious relationship to the absorption lines in the flux spectrum. Longward of 5500 Å, however, both R Boo and U Her show clear variations of ~20°–30° in position angle across the strongest absorption features, an effect which is especially pronounced in U Her. All three M-type stars show mild variations in percentage polarization at the positions of the strong bands as well, but these variations are not very marked.

R Andromedae.—Both the flux spectra of this S-type Mira star, taken at nearly the same phase in successive cycles, are similar, except that the star was about 2 magnitudes brighter at all wavelengths when observed in 1974 than in 1973. The absorption spectrum is dominated by bands of ZrO, although bands of LaO and unidentified molecular contributors are also visible, and metals contribute a few lines. As for the M-type stars, both polarization spectra show features in the blue that have no apparent relationship to the absorption features in the flux spectrum. The most striking variations in the polarization spectrum occur in the region 5000–7000 Å, where strong peaks in the percentage polarization and mild variations in position angle coincide with strong ZrO and NaI absorption. A large polarization change also occurs across the ZrO band at 9299 Å, although this appears as a dip in 1973 and as a peak in 1974.

R Leporis.—This carbon star was observed near minimum light and has almost no flux shortward of 4500 Å. Only CN bands, the sodium D lines, and terrestrial absorption bands are visible in the flux spectrum. The polarization spectrum is virtually featureless except for an abrupt change of position angle and decrease of percentage polarization below 5600 Å, and a sharp change of position angle at the D lines.

R Scuti.—This G-type RV Tauri star is much hotter than the other variable stars discussed in this paper. Serkowski (1970) has studied R Sct and concluded that the polarization due to the interstellar medium is approximately $P_U = 1.07\%$, $P_B = P_V = 1.15\%$, $\theta = 32°$. It is clear from the polarization spectrum shown here that, at the time of observation, the star showed little or no intrinsic polarization to the red of about 5500 Å, but that, to the blue of this wavelength, an increasing fraction of the polarization is intrinsic, leading primarily to a rotation of the position angle. No small-scale spectral structure is apparent in either the percentage polarization or position angle except for a possibly real drop in p coinciding with the ultraviolet Fe I lines;

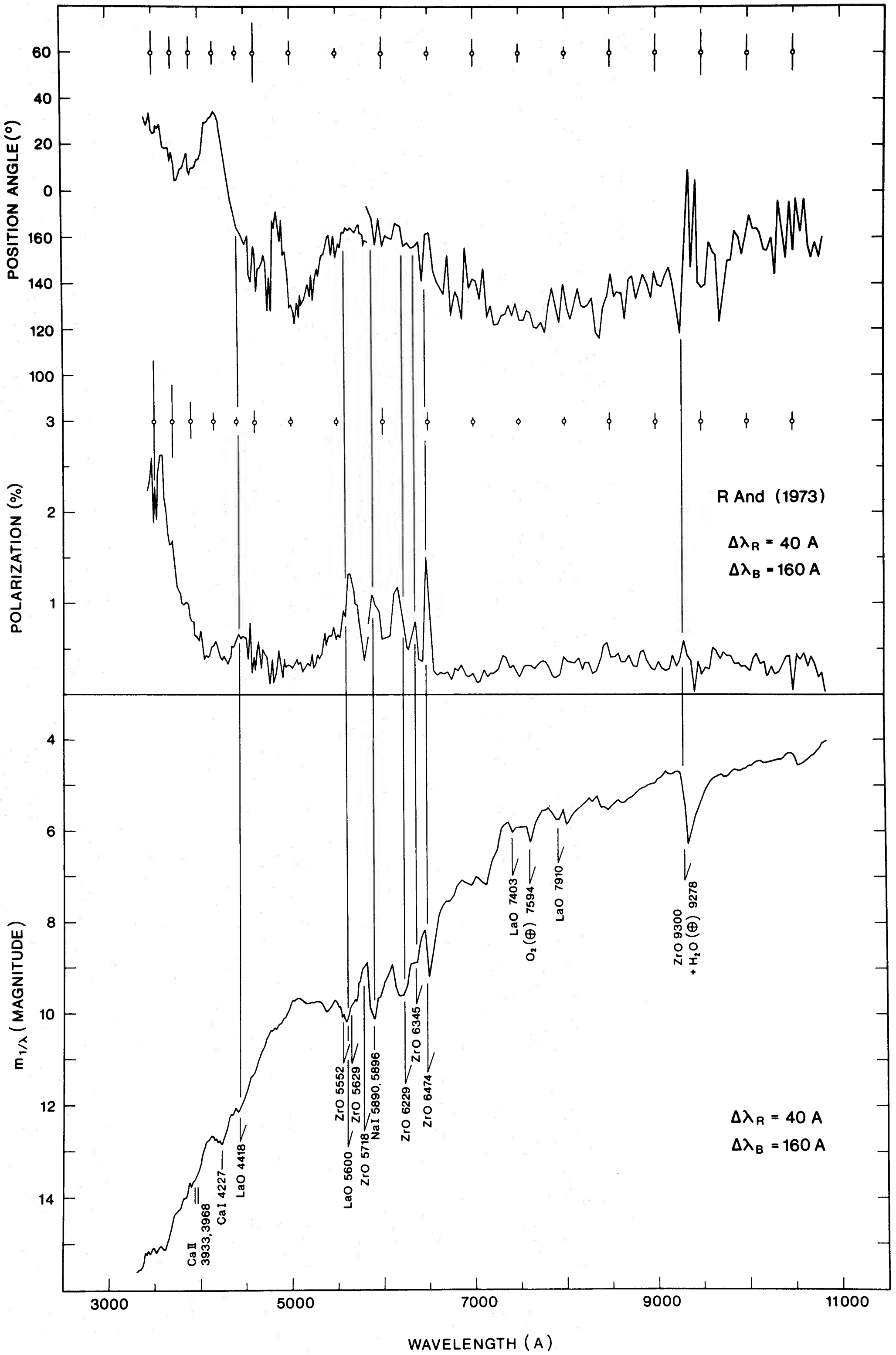

FIG. 1.—Spectrophotometric and polarimetric observations of the S-type Mira variable R And on 1973 June 22. The quantities plotted are discussed in the text.

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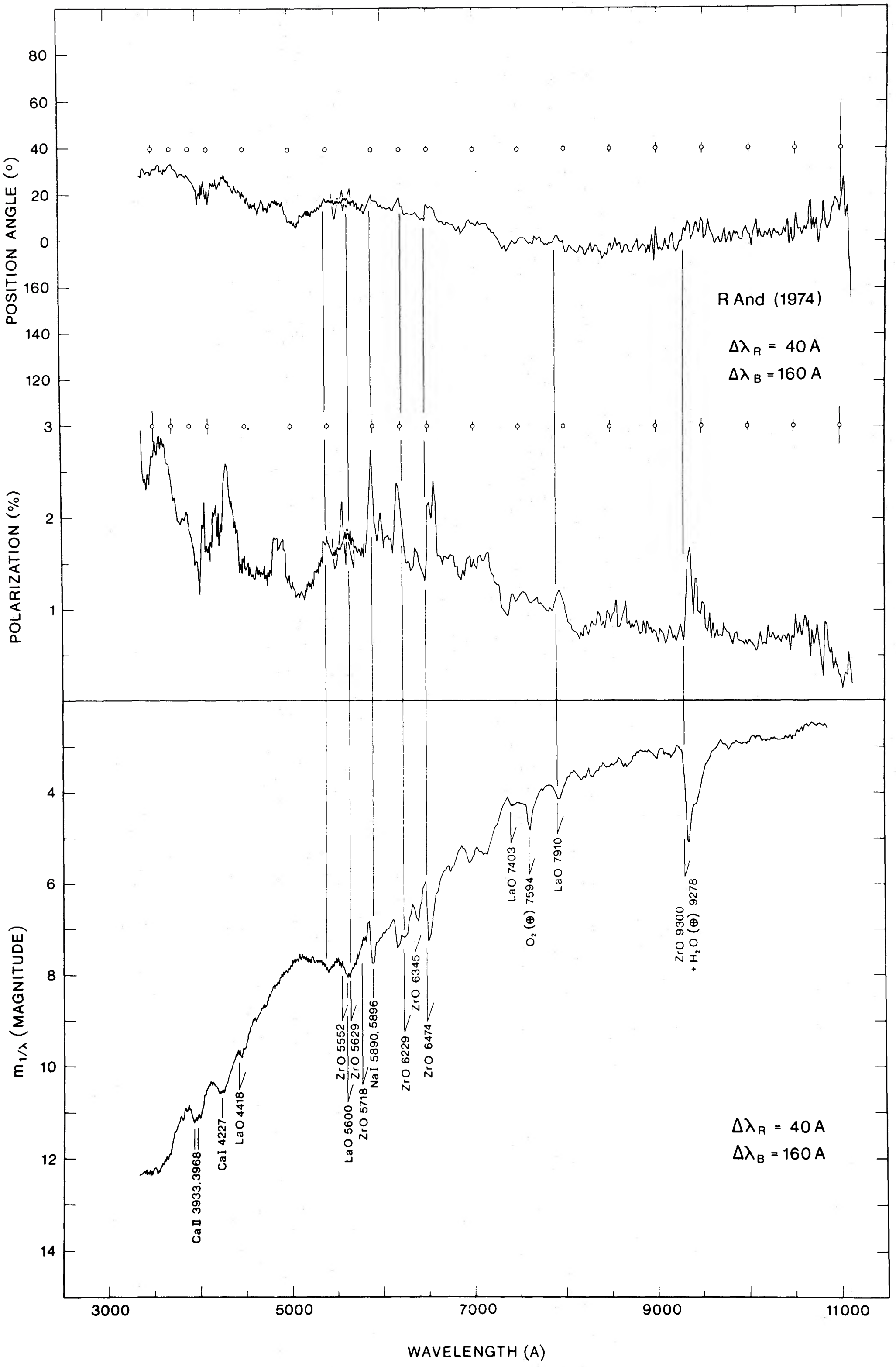

FIG. 2.—Observations of R And on 1974 September 6

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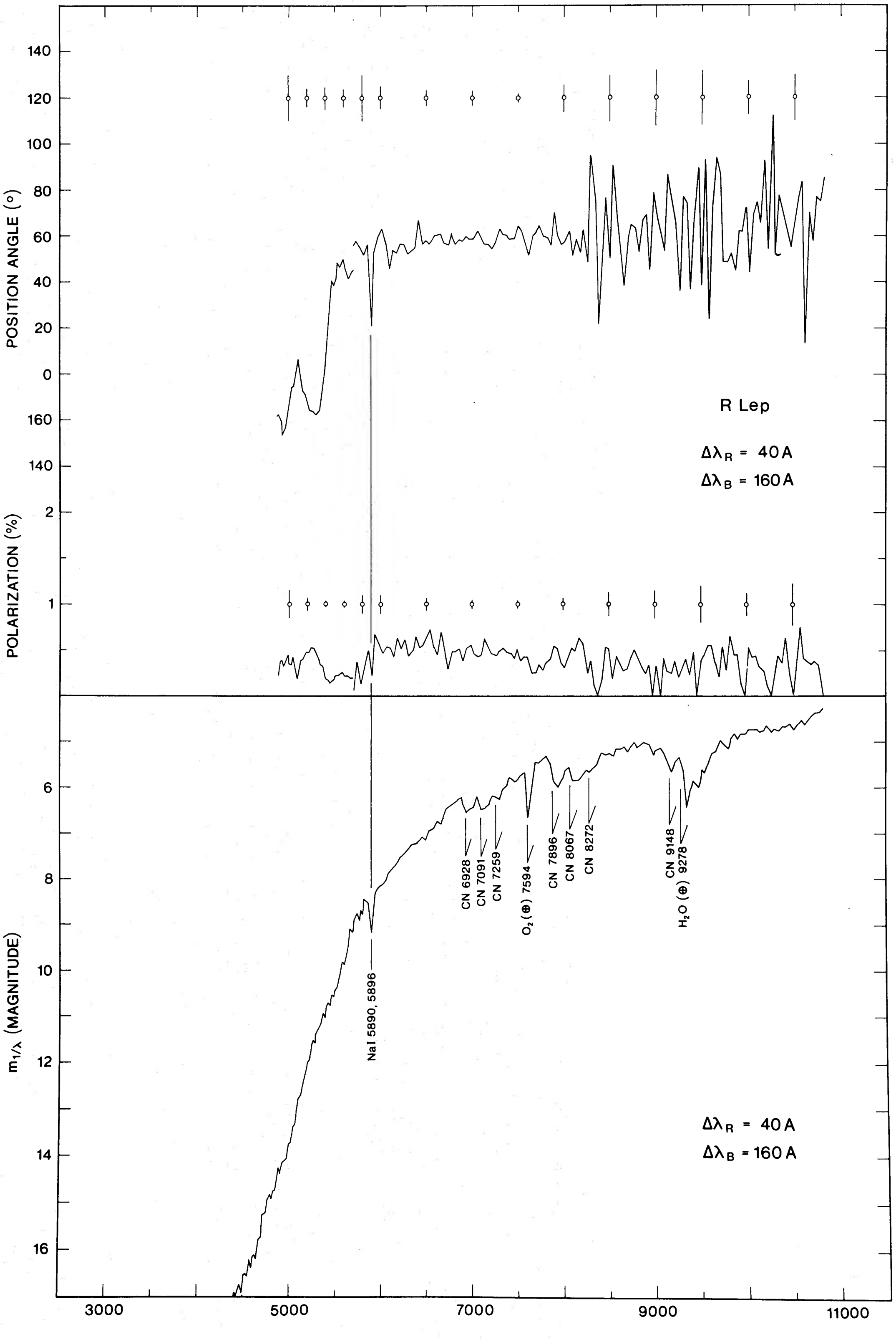

FIG. 3.—Observations of the N-type Mira variable R Lep

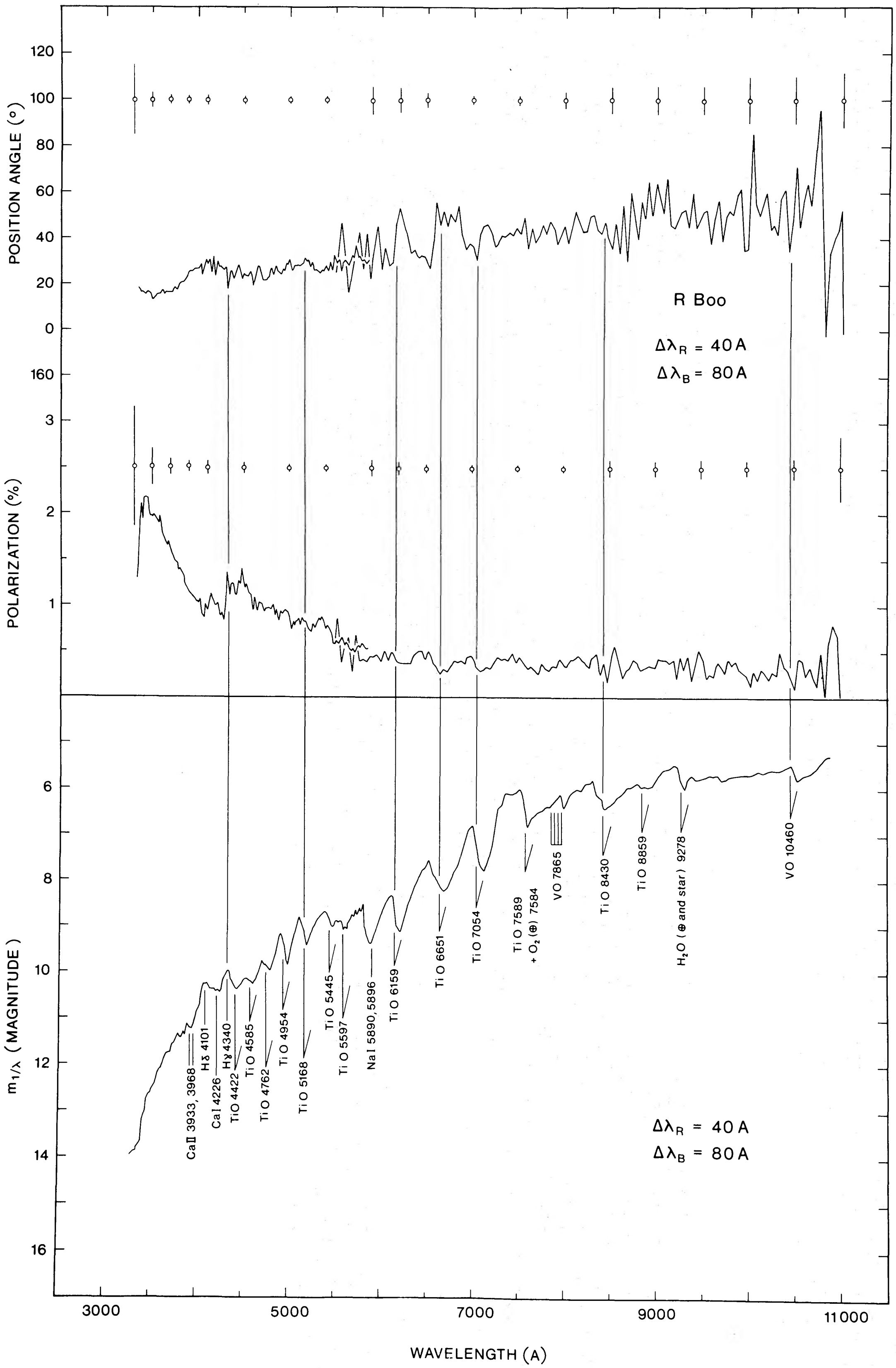

FIG. 4.—Observations of the M-type Mira variable R Boo

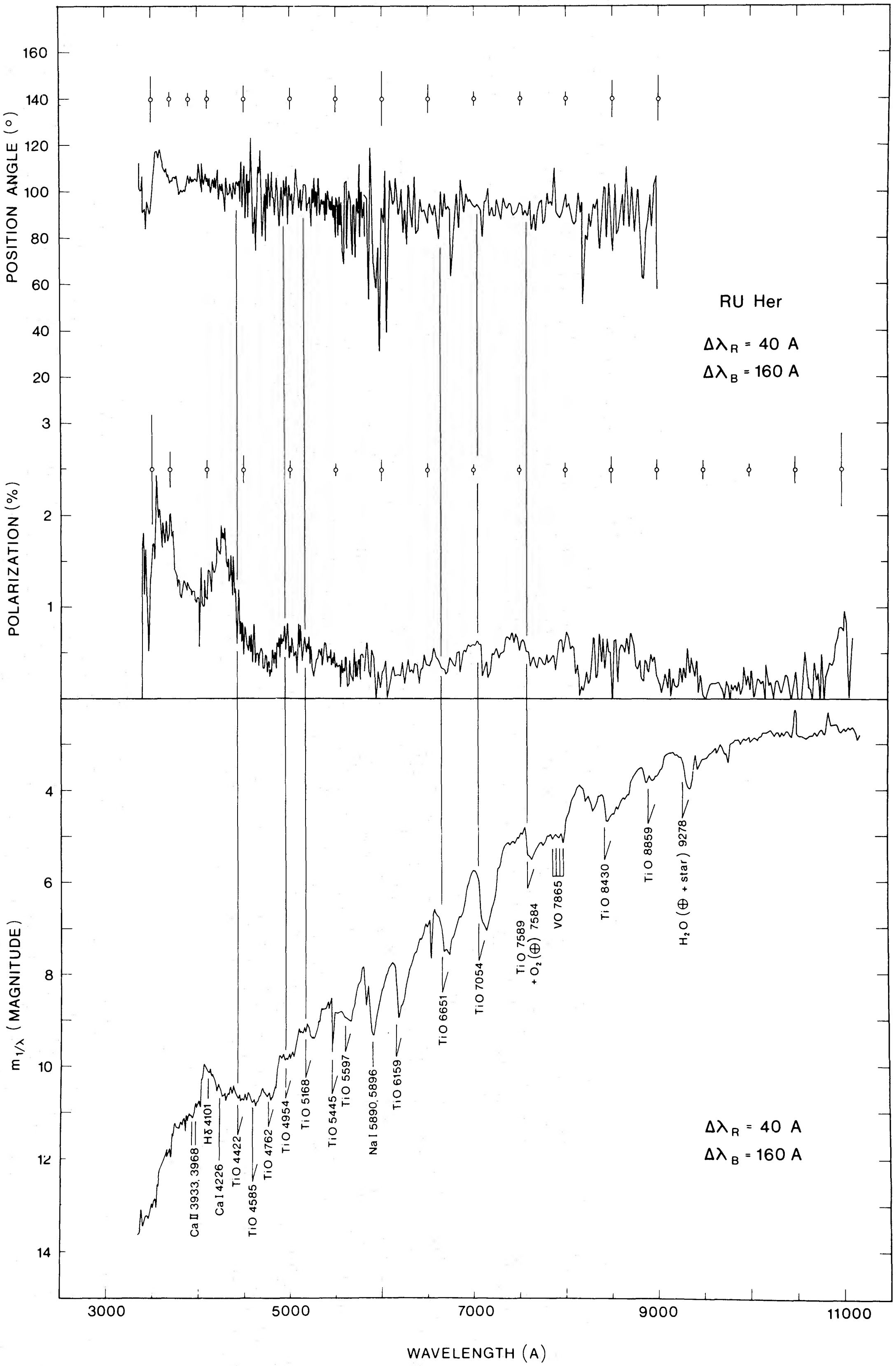

FIG. 5.—Observations of the M-type Mira variable RU Her

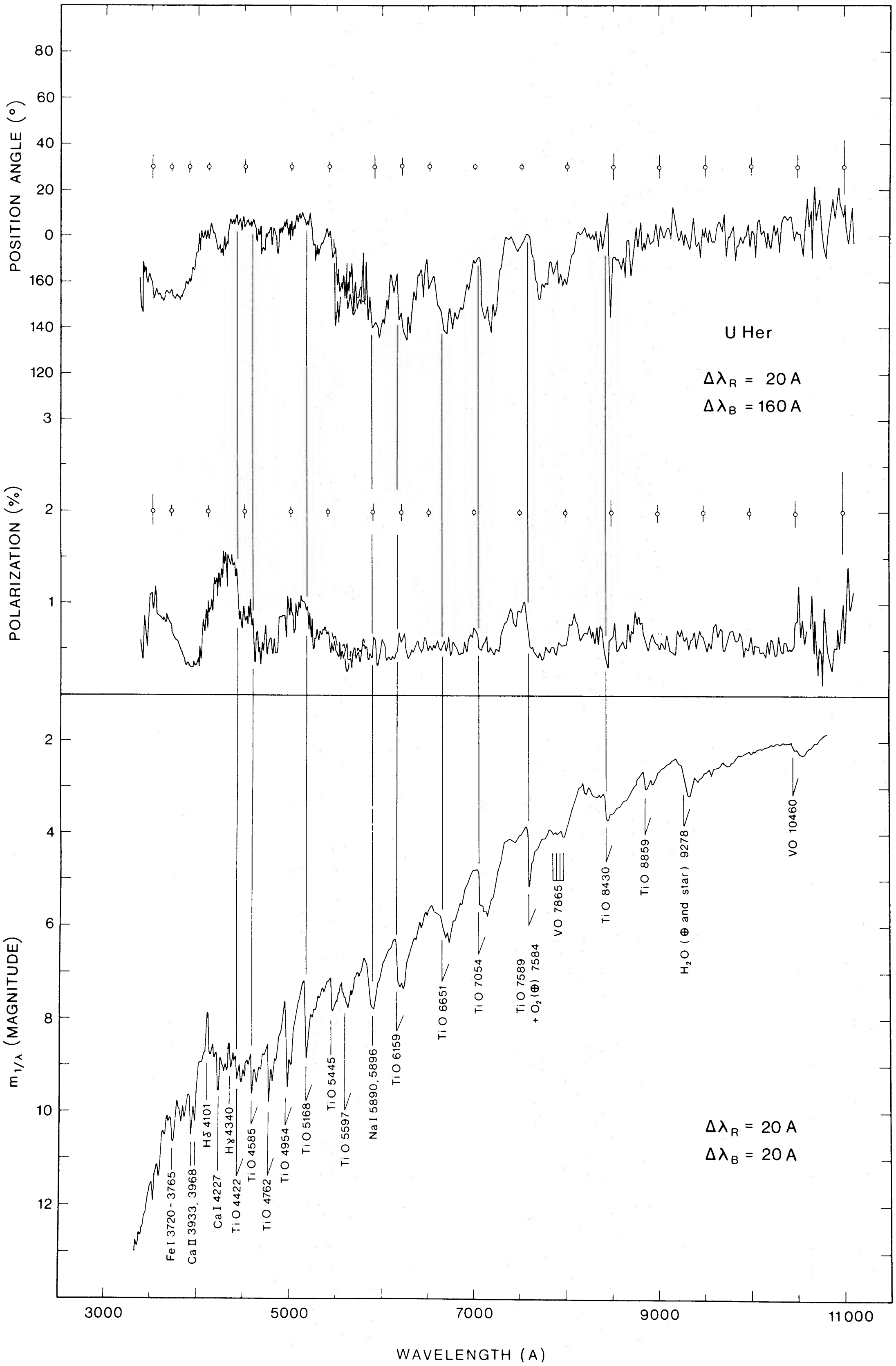

FIG. 6.—Observations of the M-type Mira variable U Her

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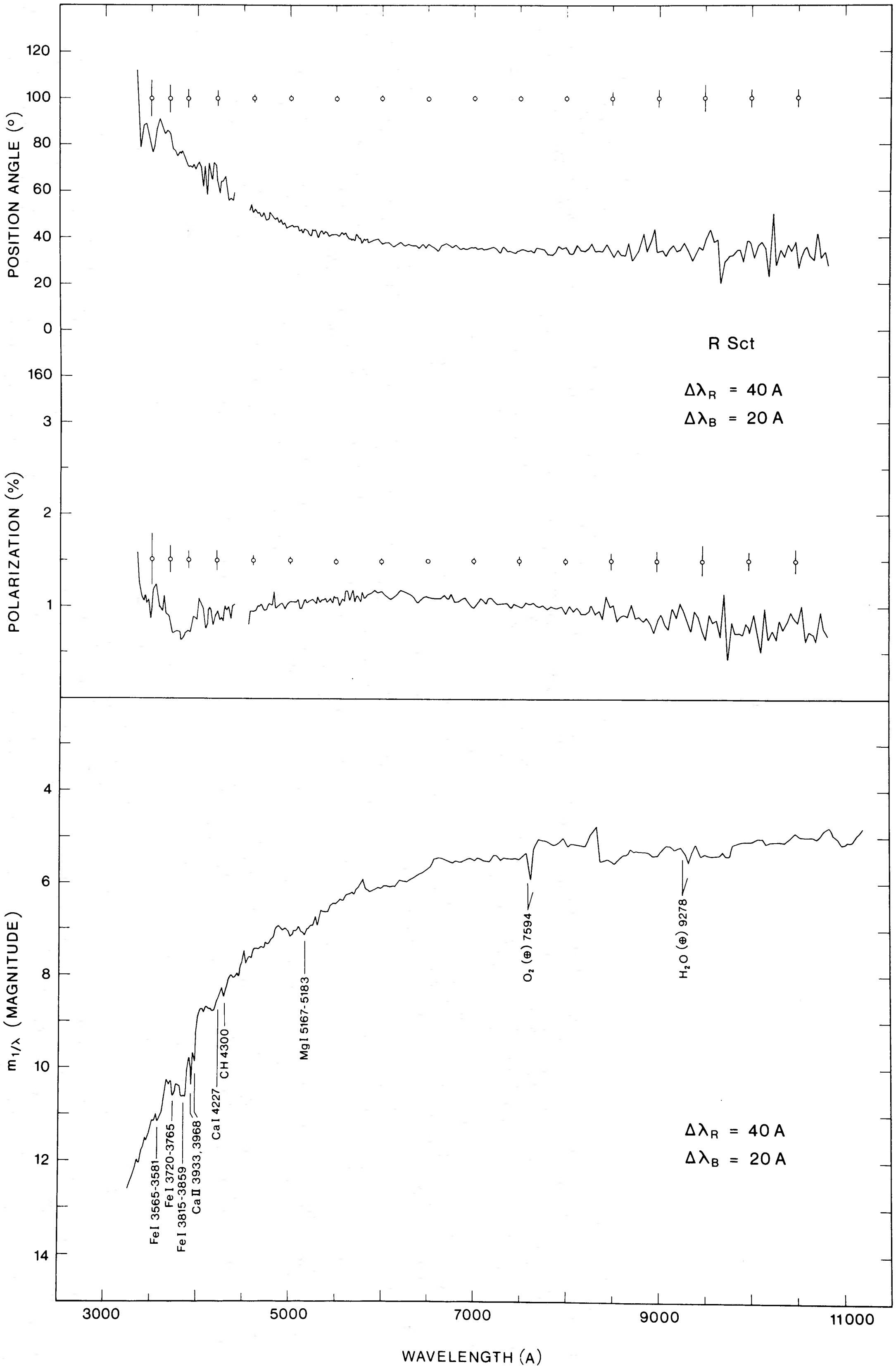

FIG. 7.—Observations of the RV Tauri variable R Sct

in the context of this paper, these data serve mainly to demonstrate that the polarization variations observed in the Mira stars are not due to instrumental errors of some sort. They incidentally indicate that the wavelength dependence of interstellar polarization is fairly free of spectral structure, a point which will be dealt with in more detail in a forthcoming paper (Angel and Landstreet 1977).

III. DISCUSSION

The strong spectral structure observed in the polarization spectra of the Mira variables discussed here, and its coincidence in the red with strong absorption features in the flux spectra, make it clear that at least some of the intrinsic polarization of these stars originates in the stellar photospheres, as proposed by Harrington (1969). This result is not necessarily in conflict with the evidence given in § I in favor of polarization by scattering in circumstellar dust shells. Each mechanism should contribute to the observed polarization if conditions are right for it to operate. Dust clouds seem to be generally present around Mira variables, judging from the 11 μm excesses measured by Dyck *et al.* (1971), but the effectiveness of such shells in producing polarization will depend on details of the geometry of the envelope; in some cases this is apparently not the most important source of polarization. In fact, the relationship between 11 μm excess and mean polarization is not very well established for Mira variables by the data of Dyck *et al.* (1971). The semiregular variables show a remarkably tight correlation, but the Miras show considerably more scatter around the mean relationship defined by the semiregular variables; in particular, a number of Miras have large 11 μm excess but low mean polarization. Thus, although dust may be the main polarization mechanism in some Mira variables, this does not always seem to be the case.

We next consider what may be the source of the asymmetry required to give net atmospheric polarization. Harrington (1969) suggested that asymmetries could arise either from the geometric effects of nonradial pulsations, or from small variations of temperature over the stellar surface. Such temperature variations may arise from an instability in which the surface develops cooler regions of grain formation, as suggested by Salpeter (1974), or from the formation of giant convection cells each of which covers an appreciable fraction of the stellar disk, as considered by Schwarzschild (1975). In some instances, the necessary asymmetry may be due to the obscuring effect of circumstellar clouds, although this would probably be associated with appreciable circumstellar polarization as well. The fact that the observed variations in polarization across absorption features sometimes occur primarily in p and sometimes in θ suggests that in some cases two different polarization mechanisms (having different principal axes) are competing to produce the observed polarization.

The observational data on time variation of polarization should, in principle, be of assistance in distinguishing these sources of asymmetry. One would expect a pulsational asymmetry to vary periodically with the photometric period. Convection and Salpeter's instability would be more random, although surely coupled to the Mira period to some degree. The data (Serkowski 1971) are not conclusive. The polarization of Mira, studied over five cycles (1966–1970), does show synchronized variations with maximum polarization occurring between minimum and maximum light, but R Hya, the only other star studied in sufficient detail, shows some cycles similar to Mira, and others quite different. Both stars, and most other Mira variables, show long-term stability of mean position angle, as would be expected if the asymmetries were coupled to a rotation axis.

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