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olarization Variations of the RV Tauri Stars

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おうし座ＲＶ型星の偏光の変動について

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要　旨

おうし座ＲＶ型変光星は，Ｆ型からＫ型にわたるスペクトル型をもつ超巨星の脈動変光星で，その変光はセファイドほど規則的ではなく，しばしば変光周期や変光の振幅が変化している．この変光星の特徴は，深い極小光度と浅い極小光度を交互に示すことで，相次ぐ２つの主極小光度の間の変光周期は，30日から150日の範囲にある．

この変光星の可視域のスペクトルに基づいた分類によれば，Ａ，Ｂ，Ｃの３つのグループに分類されている．Ａ，Ｂグループはそれぞれ酸素過剰と炭素過剰のスペクトルを示し，ＣグループはＣＨ，ＣＮ等の吸収帯が見えない点を除き，Ｂグループと似たスペクトルを示している．一方，星周圏の放つ赤外放射のエネルギー分布により，この変光星は酸素過剰および炭素過剰な星周圏ダストの放射を示す２種類に大別されている．ところが，Ｂグループの星の中に，酸素過剰な赤外放射の分布の特徴を示すものが観測されている．

そこで，両分類の関係を調べるために，国立天文台堂平観測所の91cm反射望遠鏡の多色偏光測光装置を用いて，13個のおうし座ＲＶ型変光星を観測した．ここでは，その内の７個の星の解析結果を報告する．得られた主な結論は，次のとおりである．

１）多くのおうし座ＲＶ型変光星は，固有の偏光成分を示す．

２）観測された偏光度は，極大光度時よりも極小光度時の方が大きい傾向を示す．

３）Ｂ，Ｃグループでは、観測された偏光度が，とくに極小光度時近くで0.6μm あたりで極大になる傾向を示す．

４）Ａグループに属するふたご座ＳＳ星では，固有の偏光度や偏光位置角が，極小光度時近くで波長とともに増す傾向がわずかに見られる．

Ⅰ. Introduction

The RV Tauri stars are a group of pulsational variables which lie between the cepheids and the Mira-type Variables in the HR diagram. The spectral types of these stars range from F to K, and the luminosity classes range from I to II. Their light curves are characterized by alternate deep and shallow minima. The periods defined by the interval between successive deep minima range from 30 to 150 days.

The RV Tauri stars are semiregular variables. They have a relatively regular period, but the magnitudes of the maxima and minima are not constant. Interchanges of minima sometimes occur, i.e., two deep or two shallow minima occur in succes-

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sion. On the basis of light curves they are divided into two subgroups, RVa and RVb. The RVa group is characterized by a relatively regular light curve, especially by a relatively constant magnitude of maximum, and the interchanges of minima does not occur frequently. In the RVb group the typical light curves are superimposed on a very long wave of greater amplitude. Some hundred RV Tauri stars are found in the Galaxy. They are generally thought as radial pulsators, but some investigators assert that they also perform a non-radial pulsation.

On the basis of spectroscopic characteristics in an optical region Preston et al. (1963)[1] divided the RV Tauri stars into three subgroups, group A, group B, and group C. The group A(GK-type) generally shows anomalously strong TiO bands at light minima whose strength corresponds to early M-type supergiants, while intensities of metallic lines indicate the type G or K. The group B(Fp(R)-type) shows spectra to which a definite spectral type, in ordinary sense, cannot be assigned. The most distinctive characteristic in the spectra of the group B is that the CH and CN bands show considerable change with phase. Near light minima these bands appear with considerable strength indicative of an enhanced carbon abundance. The group C shows all the characteristics of the group B except that the carbon features are weak or not present. Dawson (1979)[2] divided the group A into two groups, group A_1 and group A_2. The group A_1 shows TiO bands near light minima, while the group A_2 have not been known to show TiO bands at any phase.

The RV Tauri stars show strong excess infrared radiation, which indicates thay are embedded in circumstellar dust envelopes. For example, Gehrz(1972)[3] observed that U Mon and RV Tau, both of which bvelong to the group A_1 show silicate emission features at 10 and 18μ while AC Her, which belongs to the group B, shows unidentified emission features at $8-13\mu$. His observation seemed to suggest that there is good correlation between the optical spectra and infrared spectra. The group A whose optical spectra indicate oxygen-rich abundances also shows the infrared spectra indicative of oxygen-rich circumstellar dust, and the group B whose optical spectra indicate carbon-rich abundances shows the infrared spectra with the unidentified emission features. But this correlation was not supported by the observations made after Gehrz(1972)[3]. For example, Gehrz and Ney(1972)[4] observed the infrared spectra of four southern RV Tauri stars, IW Car, RU Cen, SX Cen, and AR Pup. He found that the infrared spectra of IW Car, SX Cen, and AR Pub are similar to that of the oxygen-rich RV Tauri star RV Tau, and the infrared spectrum of RU Cen is similar to that of the carbon-rich RV Tauri star AC Her. On the other hand, Lloyd Evans(1974)[5] observed the optical spectra of the above four stars and found that all of the stars belong to the group B. Thus, there are the RV Tauri stars which simultaneously show the carbon-rich optical spectra and the oxygen-rich infrared spectra. Furthermore, Gehrz (1972)[3] observed that TW Cam, DF Cyg, SU Gem, TT Oph, R Sge, and V Vul, all of which belong to the group A, show the infrared spectra different from that of RV Tau, i.e., their spectra have smooth, featureless, non-Planckian continua.

Multicolor polarimetric observations of the RV Tauri stars were made in this paper. The main purpose of the observations is to investigate the structures of the photospheres and circumstellar dust envelopes of the RV Tauri stars and to clarify the relationship between the optical spectra and the infrared spectra.

II. Observations and Reductions

The multicolor polarimetric observations reported in this paper were obtained between 1993 October 23 and 1994 April 16. The 91cm reflector at the Dodaira Station of the National Astronomical Obsevatory was used with the multi-channel polarimeter. This polarimeter can measure linear polarization simultaneously at eight effective wavelengths of 0.36, 0.42, 0.455, 0.53, 0.64, 0.69, 0.76, and 0.88μm. The construction and operation of this polarimeter are described by Kikuchi(1988)[6]. A Wollaston prism is used as a polarizer. For a reduction of the effects due to the atmospheric scintillation, an achromatic half-wave plate in front of the Wollaston prism rotates with a frequency of 20 Hz. For a subtraction of the sky background, the exchanging diaphragm method is used, where in the course of measurements a pair of circular diaphragms of different apertures are exchanged with an interval of typically several seconds. In this observation, the diameter of a smaller diaphragm is equal to 1.5mm and that of a larger one is equal to 3.0mm, which correspond to the angular diameters of 19 and 37arcsec, respectively.

The instrumental polarization is determined by observations of unpolarized stars listed by Serkowski(1974)[7]. The stability of the position angle of polarization is checked by observations of strongly polarized stars also listed by Serkowski (1974)[7]. The correction for the depolarization effect within the instrument is made by observations with a Glan-Taylor prism inserted in front of the diaphragm. With the above correction procedures, an accuracy of better than 0.03% is obtained.

By observations with the above instrument, we obtained the degree of linear polarization p and the position angle of polarization θ. We also obtained the normalized Stokes parameters Q and U, where there are the following relations :

$$Q=p \cos 2\theta, \quad (1)$$

and $$U=p \sin 2\theta. \quad (2)$$

The program by Hirata (1993)[8] was used for the reductions of the raw data into the quantities of p, θ, Q, and U.

Thirteen RV Tauri stars and three related stars were observed in this study. These stars are listed in table 1. In this table, six stars underlined, TW Cam, SS Gem, AC Her, U Mon, R Sct, and V Vul have been observed polarimetrically, and the other stars were newly observed polarimetrically in the present study.

In this paper, the results and conclusions obtained from the present observations are reported for the seven RV Tauri stars, TW Cam, UY CMa, V360 Cyg, SS Gem, SU Gem, AC Her, and EP Lyr and for the W Virginis star, CO Aur.

III. Results

The details of the results are as follows.

a) CO Aur

In the General Catalogue of Variable Stars (Kholopov et al. 1985)[9], CO Aur is classified as W Virginis star.

Three observations were made for this star on 1993 October 27/28, 1993 November 27/28, and 1993 December 24/25. Except for the channel 1 (0.36μm) and the channel 8 (0.88μm) of the polarimeter, the values of p are always smaller than 0.3% and p and θ show neither variation with time nor dependence on wavalength. As the accuracies of observations for the channels 1 and 8 are low, the time variations and the wavelength dependences for these channels cannot be considered significant. Thus, the observations do not detect the intrinsic polarization of this star.

b) TW Cam

TW Cam was observed once on 1993 December 23/24. Except for the channels 1 and 8, neither p nor θ shows a wavelength dependence. Except for the above channels the values of p are within the range from 3.0% to 3.5%, and the values of θ are within the range from 137° to 146° for all the channels.

TW Cam has been observed polarimetrically by Nook et al. (1990)[10]. They observed once on 1986 December 4/5 when TW Cam was just before secondary light maximum. They detected wavelength dependences of Q and θ. As the wavelength increases from 0.4828μm to 0.6877μm, the value of Q increases from −0.59% to 0.08% and the value of θ increases from 129° to 136°. Furthermore, they determined the interstellar linear polarization of the region near TW Cam on the basis of the near-neighbor method described by Bastien (1985)[11]. The interstellar polarization determined by them are given as follows:

$$p_{max}=2.97\pm1.0\%,\quad \theta=135^\circ.8\pm4^\circ,\ \text{and}\ \lambda_{max}=0.52\mu m, \qquad (3)$$

where p_{max} is the maximum polarization which occurs at the wavelength λ_{max}. They adopted the empirical formula given by Wilking, Lebofsky, and Rieke (1982)[12] (hereafter referred to as WLR) for a wavelength dependence of the interstellar linear polarization, which is given as follows:

$$p=p_{max}\cdot\exp\left[-K\ln^2(\lambda_{max}/\lambda)\right], \qquad (4)$$

where K is a linear function of λ_{max}:

$$K = -0.10 + 1.86\lambda_{max}. \quad (5)$$

By removing the above interstellar polarization from the observed polarization, they yielded the intrinsic polarization of TW Cam. They found that for the intrinsic polarization the values of p are proportional to λ^{-4} and the values of θ do not depend on wavelength.

Our observation does not agree with their observation. For example, neither Q nor θ depends on wavelength in our observation. Furthermore, in our observation, the values of U are smaller by about 0.3% and the values of Q are larger by more than 1.0%. The intrinsic polarization of TW Cam obtained in our observation is listed in table 2, which is yielded by removing the same interstellar polarization

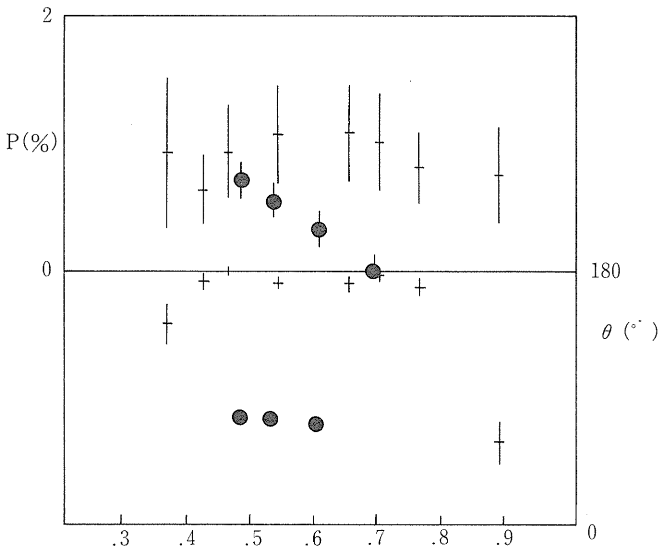

Fig.1. Intrinsic Polarization of TW Cam. Our results are represented with the error bars. The filled circles represent the results by Nook et al. (1990)[10].

that they adopted. As is shown in figure 1, our result differs markedly from their result. Our values of p have a maximum near 0.6μm and our values of θ are larger than their values by about 100°. As the author does not have data on the light curve of TW Cam, the phase at which our observation was made is uncertain. But the visual magnitude +9.9th mag., which is larger than that of their observation by about 0.3 mag. Therefore, it seems that the phase of our observation differ from that of their observation, and the discrepancy between our result and their result may be due to the difference in phase.

c) UY CMa

Three observations were made for UY CMa on 1993 December 27/28, 1994 March 31/April 1, and 1994 April 4/5. Our observations show both a time variation and a wavelength dependence. For example, except for the channels 1 and 8, the values of p observed on 1993 December 27/28 and 1994 March 31/April 1 take a maximum at the channel 6 (0.69μm), but the values on 1994 April 4/5 take a minimum at the channel 6. Furthermore, the values for the eight channels are relatively scattered in the QU plane, and the distribution of the plots in this plane varies relatively with time. As this star was relatively dim(m_V>11) when it was observed, observational errors are large. However, as is shown in figure 2, at least, the time variation of

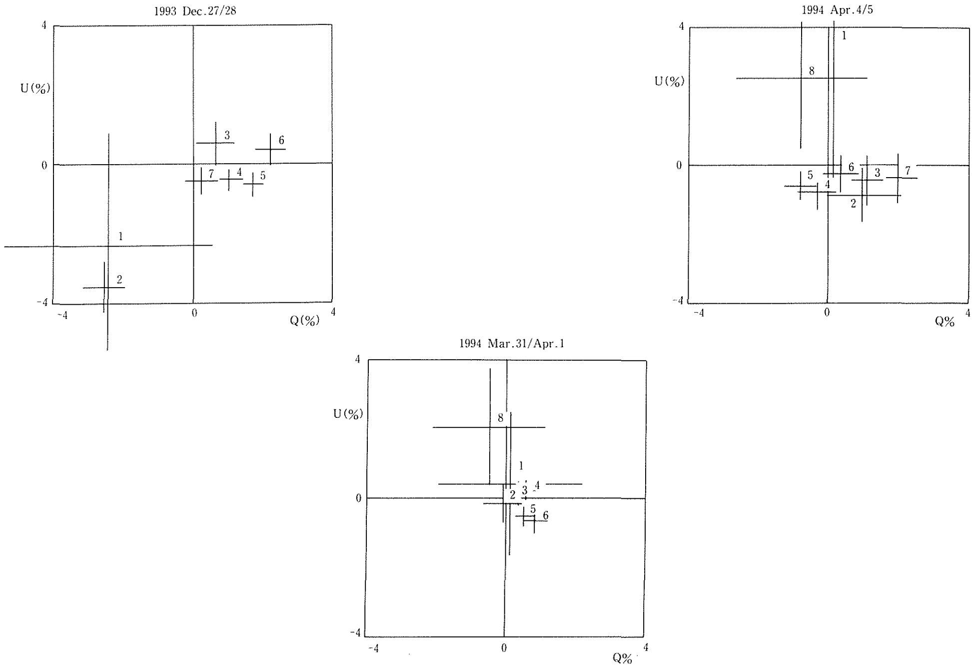

Fig.2. QU Plane for the Observed Polarization of UY CMa. The positions for the eight channels are shown with the error bars.

the channel 2 (0.42μm) seems to be true, because the differences in the position in the QU plane are equal to or greater than three times the standard deviation of measurements (3σ). Thus, we consider that the time variation of this satar is likely true.

d) V360 CMa

V360 CMa was observed once on 1993 October 24/25. According to a visual light curve by the Japan Astronomical Study Association (hereafter referred to as JASA) which was communicated to the author by Saijo(1994)[13], the phase at which the observation was made corresponds to that of shortly after primary light maximum. Except for the channels 1, 7 (0.76μm), and 8, the values of p are smaller than 0.9%. Both p and θ show wavelength dependences, and the values for the eight channels are somewhat scattered in the QU plane. However, most of the differences are smaller than 3σ, we do not consider the wavelength dependences significant.

e) SS Gem

Four observations were made for SS Gem on 1993 November 27/28, 1993 December 23/24, 1994 February 2/3, and 1994 February 19/20. Except for the channels 1, 2, and 8, neither significant time variation nor significant wavelength dependence is observed. Except for the above channels, the values of p are within the range from 2.7% to 3.1%, and the values of θ are within the range from -2° to 3°. Only the channel 2 shows significant time variations of Q, U, and p, which are larger than 4σ. For example, the p value on 1994 February 2/3 are greater than the other values by more than 0.4%, and the U Values on 1994 February 2/3 and 1994 February 19/20 are smaller than the other values by more than 0.5%. According to the visual light curve by JASA, the phase on 1994 February 2/3 corresponds to that of shortly after primary light minimum, while the other phases correspond to that of light maximum. Thus, the time variations for the channel 2 may be due to the difference in phase.

SS Gem has been observed polarimetrically by Wolf(1972)[14] and Nook et al. (1990)[10]. Wolf(1972)[14] observed once on 1969 December 17/18. His observation agrees approximately with our observations. Nook et al. (1990)[10] observed twice on 1986 November 28/29 and 1987 February 17/18 when SS Gem was near secondary light minimum. Their observations also agree approximately with our observations. They determined the interstellar linear polarization of the region near SS Gem on the basis of the near-neighbor method, which are given as follows:

$$p_{max}=2.25\pm1.0\%,\ \theta=170^\circ\pm10^\circ,\ \text{and}\ \lambda_{max}=0.54\pm0.04\mu\text{m}. \quad (6)$$

They yielded the intrinsic polarization of SS Gem, by adopting the above values of p_{max}, θ, and λ_{max} and the formula by WLR. They concluded that no evidence exists for an intrinsic polarization, because both the observed values of p and θ are within 1σ of the interstellar polarization.

The intrinsic polarizations of this star are yielded from our observations by removing the same interstellar polarization that Nook et al. (1990)[10] adopted. As is shown in figure 3, the intrinsic polarization on 1994 February 2/3 is slightly different form those on the other dates, though the differences are within 3σ. There remains a possibility that the interstellar polarization might agree with the observed polarizations by increasing the value of p_{max}. Further observations are necessary in

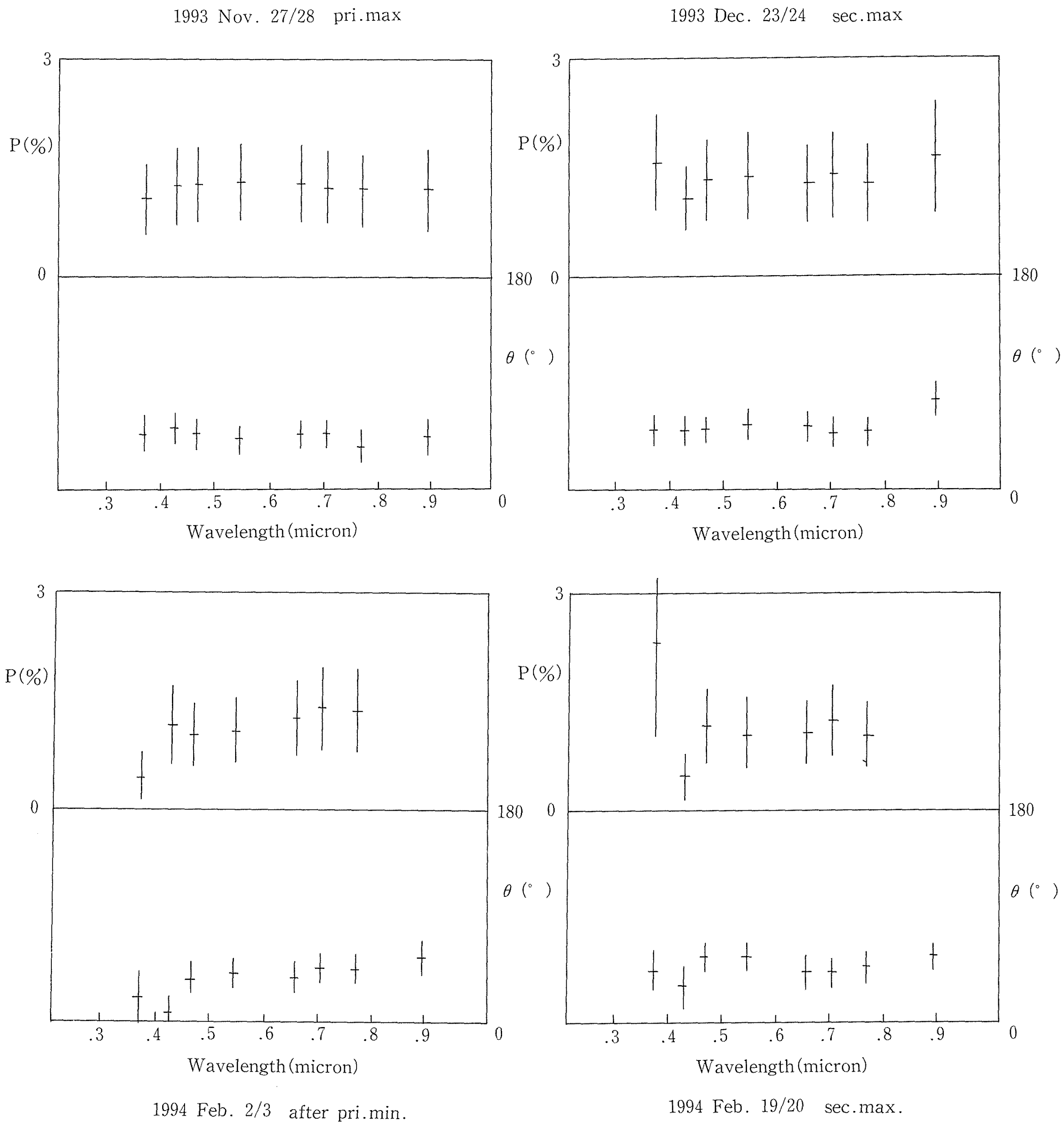

Fig.3. Intrinsic Polarization of SS Gem. The phases of a light curve as well as the observational dates are noted.

order to obtain the conclusion about the existence of the intrinsic polarization.

f) SU Gem

Four Observations were made for SU Gem on 1993 December 24/25, 1993 December 26/27, 1993 December 27/28, and 1994 March 29/30. The first two observations are not reliable, because observational errors are very large. Compared with the observation on 1993 December 27/28, the observation on 1994 March 29/30 gives the larger values of p and smaller values of Q and U, while, except for the channels 1, 2, and 8 , it gives nearly the same values of θ ($120^\circ < \theta < 140^\circ$). According to the visual light curve by JASA, the phase on the last observation corresponds to that of light minimum, while the other phases correspond to that of light maximum. Thus, the above observational differences may be due to the difference in phase. Since the observational errors on the last two observations are relatively large, further observations are necessary in order to confirm the time variation in polarization of this star.

g) AC Her

Four observations were made for AC Her on 1993 November 24/25, 1994 February 23/24, 1994 March 29/30, and 1994 April 15/16. The values of θ decreases with wavelength, especially from the channel 1 to the channel 4. There is a time variation in the wavelength dependence of the p values. For example, as is shown in figure 4, the p value on 1994 February 23/24 are approximately equal, while the p values on 1994 April 15/16 take a maximum near the channels 4 and 5 (0.64μm). The distributions on the other dates are intermediate between those on the above two dates. According to the visual light curve by JASA, the phase on the last observation corresponds to that of primary light mimimum, while the other phases are those other than light minimum. Thus, the time variation is probably due to the difference in phase.

AC Her has been observed polarimetrically by Shakhovskoi(1964),[15] Hensen et al. (1985),[16] and Nook et al. (1990).[10] Shakhovskoi(1964)[15] observed between 1961 June 11 and 1961 November 25. He observed the time variation of polarization. The values of p and θ observed by him are within the ranges from 0.2% to 0.8% and from 10° to 60°, respectively. The p and θ values for our observations are within the above ranges, except for the p values on 1994 April 15/16. Hensen et al. (1985)[16] obserbed in the B and V bands between 1982 September 4 and 1982 November 24. They observed the variation of polarization with phase. According to their observations, the value of U in the B band becomes larger than 1.0% near primary light minimum, which result are also obtained in our observations. The values of Q in the B band are smaller than -0.2% near primary light minimum, while our corre-

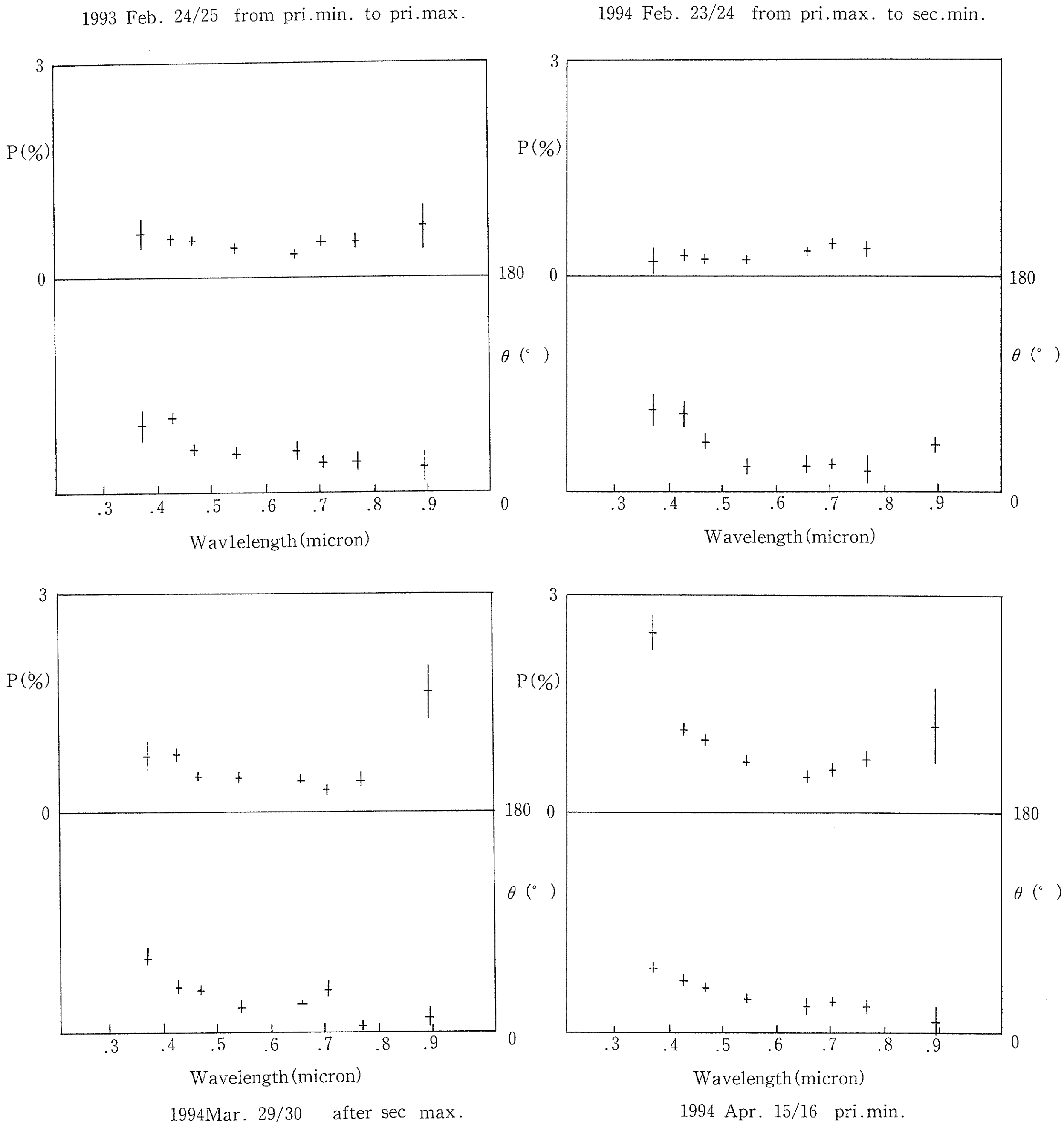

Fig.4. Observed Polarization of AC Her.

sponding values for the channels 2 and 3 are larger than 0.1%. According to them, the repeatability of the Q values from cycle to cycle is not so good as that of the U values. Nook et al.(1990)[10] observed six times between 1987 April 8 and 1987 August 20. They also observed the variation of polarization with phase. The variation observed by them correspond approximately with that observed by the author. For example, among the six observations by them the most similar one to our observation on 1994 April 15/16 is that made near primary light minimum. Especially, our values of Q agree approximately with their values.

h) EP Lyr

Two observations were made for EP Lyr on 1993 October 24/25 and 1993 November 24/25. The first observation is not reliable, bacause observational errors are very large. According to the visual light curve by JASA, the phase on the last observation corresponds to that of shortly before primary light minimum. As is

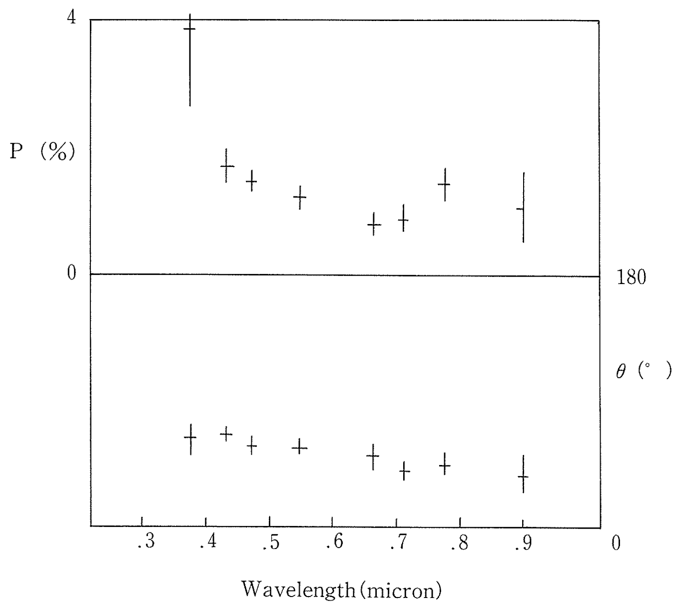

Fig.5. Observed Polarization of EP Lyr on 1993 November 24/25.

shown in figure 5, the p values on the last observation take a minimum at the channel 5, and the values of θ decrease slightly with wavelength.

III. Discussion

We cannot obtain the conclusion concerning directly with the main purpose of the present study from the above results. However, the following conclusions are obtained from the above results.

1) Our observations for SS Gem and AC Her agree with those made before by other observers. This indicates that our observations made at the Dodaira Station of the National Astronomical Observatory give consistent results with those obtained at other observatories. Although our observation for TW Cam does not agree with that by Nook et al. (1990)[10], it can be explained by the deffernce in phase.

2) The results as to the time variation of polarization obtained from our observations are summarized in table 3. In this table, Confirmed Stars are the stars whose time variations for many channels are greater than 3σ; Possible Stars are the stars which show time variations but the ranges of variations are smaller than 3σ; Unknown Stars are the stars which are observed only once or the stars which are observed two times but an error of one observation is too large to draw a significant result; Underlined stars are the stars whose time variations have been observed by other observations. As is indicated by this table, many of the RV Tauri stars observed show the time variations of polarization. There is even the possibility that all of the RV Tauri stars observed show the time variation. The time variation of an observed polarization means that the observed polarization includes an intrinsic component of the observed star, because the interstellar polarization does not vary with time. Therefore, it can be concluded that many RV Tauri stars have an intrinsic polarization and all the RV Tauri stars may have an intrinsic polarization.

3) The RV Tauri stars observed more than two times show a tendency for the observed value of p at light minimum to be larger than that at light maximum, as has been observed by other observations.

4) The RV Tauri stars belonging to the group B or C show a tendency for the observed value of p to take a maximum at the channel 4 or 5, especially at light minimum.

5) As is shown in figure 3, for SS Gem belonging to A_2 group, the intrinsic values of p and θ near light minimum have a slight tendency to increase with wavelength, though the differences are within 1σ.

The analysis of the observational data for remaining eight stars observed in the present study are being made. Further multicolor polarimetric observations for RV Tauri stars are also being made at the Dodaira Station of the National Astronomical Observatory in order to achieve the main purpose of the present study.

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Table 1. Data on the Stars Observed. The second column gives the classification in the General Catalogue of Variable Stars (Kholopov et al. 1985).[9] The third column gives the classification on the basis of optical spectra. Underlined stars have been observed polarimetrically before the present observations.

Star	Variable Star Class	Optical Group	Period (days)	Mean m_v
CO Aur	CW		1.8	7.8
TW Cam	RVa	A_2	85.6	9.6
UY CMa	RVa	B	113.9	10.7
V360 Cyg	RVa	C	70.5	11.4
SS Gem	RVa	A_2	89.3	8.9
SU Gem	RVb	A_2	50.1	11.4
AC Her	RVa	B	75.5	7.5
EP Lyr	RVb	B	83.3	10.5
U Mon	RVb	A_1	92.3	6.3
TT Oph	RVa	A_2	61.1	10.2
EI Peg	SRa		61.2	9.9
R Sct	RVa	A_1	140.2	5.8
Z Sex	Lb			9.4
R Sge	RVb	A_2	70.6	9.2
RV Tau	RVb	A_1	78.7	9.2
V Vul	RVa	A_1	75.7	8.4

Table 2. Intrinsic Polarization of TW Cam.

No. of the Channel	Wavalength (μm)	Q (%)	U (%)	p (%)	θ (%)
1	0.36	0.24±0.46	−0.89±0.59	0.92±0.58	142°.4±14°.5
2	0.42	0.61±0.26	−0.17±0.12	0.63±0.25	172.4± 6.2
3	0.455	0.93±0.35	−0.01±0.08	0.93±0.35	179.8± 2.5
4	0.53	1.03±0.38	−0.31±0.13	1.07±0.37	171.6± 4.4
5	0.64	1.03±0.38	−0.34±0.13	1.08±0.37	170.9± 4.5
6	0.69	1.00±0.37	−0.10±0.11	1.01±0.37	177.2± 3.2
7	0.76	0.76±0.29	−0.30±0.13	0.81±0.27	169.2± 5.6
8	0.88	0.40±0.35	0.65±0.36	0.76±0.36	57.9±13.4

Table 3. Results as to the Time Variation of Polarization.

Confirmed Stars	TW Cam	AC Her	
Possible Stars	UY CMa	SS Gem	SU Gem
Unknown Stars	V360 Cyg	EP Lyr	

(平成 6 年11月 7 日受理)