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わし座AD星とこぎつね座V星の固有偏光の特徴について

吉　岡　一　男[1)]

Features of Intrinsic Polarization of AD Aql and V Vul

Kazuo YOSHIOKA

要　旨

おうし座RV型星は、主極小と副極小を交互にくり返す光度変化に特徴がある半規則的な変光星である。この変光星は、可視域のスペクトルをもとに、酸素過剰なＡグループと炭素過剰なＢ、Ｃグループに細分類されている。

われわれは、国立天文台堂平観測所の91cm反射望遠鏡を用いて、おうし座RV型星の多色偏光観測を行った。観測された17個の星の内、15個に対してはすでに星間偏光成分を取り除いて固有偏光成分を求めている。

本論文では、残りの２個の星、わし座AD星とこぎつね座Ｖ星に対して固有偏光成分を求めた。星間偏光成分はnear-neighbor法を一部変えた方法で求めた。その結果、両星とも固有偏光位置角には明確な波長依存性は見られないが、固有偏光度に関しては、わし座AD星では中央の波長域で極大値をとる傾向がわずかに見られるのに対して、こぎつね座Ｖ星ではいろいろな波長依存性が見られる。

さらに、これまでに得られた17個の星の固有偏光成分の特徴を概観し、その解釈を述べた。とくに、Ｂグループの星のまわりを２層以上の星周圏ダストが囲んでいる可能性やＣグループには星周圏ダストが存在しない可能性があることを指摘した。

ABSTRACT

The RV Tauri stars are semiregular variables whose light curves are characterized by alternate deep and shallow minima. On the basis of spectroscopic characteristics in an optical region the RV Tauri stars are divided into the oxygen-rich group, the group A, and the carbon-rich group, the group B and the group C.

We made the multicolor polarimetric observations of 17 RV Tauri stars, using the 91cm reflector at the Dodaira Station on the National Astronomical Observatory. Among the 17 stars we have already obtained the intrinsic polarization of 15 stars by removing the interstellar polarizations.

In this paper we report the intrinsic polarizations of the other two stars, AD Aql and V Vul. The interstellar polarizations are determined by the modified near-neighbor method. As a result, the position angles of intrinsic polarization of both stars do not show a notable wavelength dependence. The degree of intrinsic polarization for AD Aql shows slightly a tendency to take a maximum at an intermediate wavelength, while those for V Vul show various wavelength dependences.

Furthermore, we surveyed the general features of intrinsic polarizations for RV Tauri Stars observed by us, and described the interpretations of these features. Especially, we suggested that the B group stars have more than two circumstellar dust envelopes, and that the C group stars have no circumstellar dust envelope.

Ⅰ．Introduction

The RV Tauri stars are semiregular variables which lie between the Cepheid and the Mira-type variables in the HR diagram. Their light curves are characterized by alternate deep and shallow minima. The periods between two adjacent deep minima, which are called double periods or formal periods, range between 30 to 150 days.

On the basis of light curves the RV Tauri stars are divided into 2 subgroups, RVa and RVb. The RVa

1) 放送大学助教授（「自然の理解」専攻）

group is characterized by a relatively regular light curves, and the interchanges of minima do not occur frequently. The RVb group is characterized by a rather irregular light curve, especially by a superposition of a long-term brightness variation.

On the basis of spectroscopic characteristics in an optical region Preston et al. (1963)[1] divided the RV Tauri stars into 3 subgroups, group A, group B, and group C. The group A generally shows anomalously strong TiO bands at light minima whose strength corresponds to early M-type supergiants. The group B shows CH and CN bands near light minima 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 (1797)[2] divided the group A into the group A_1 and A_2. The group A_1 shows TiO bands near light minima, while the group A_2 does not show TiO bands at any phase.

The RV Tauri stars show strong excess infrared radiation, which indicates that they are embedded in circumstellar dust envelopes (hereafter referred to as CDE). The RV Tauri stars are generally regarded as post-asymptotic giant branch (hereafter referred to as post-AGB) stars which left the AGB recently. Their CDE's are thought to be formed as a result of mass loss at the final stage of the AGB phase (Jura (1986)[3]).

The author, together with Dr.Saijo and Associated Prof.H.Sato, has made the multicolor polarimetric observations of 17 RV Tauri stars between 1993 October 23 and 1998 October 29, using the multi-channel polarimeter attached to the 91cm reflector at the Dodaira Station of the National Astronomical Observatory.

We had obtained the intrinsic polarizations for 15 RV Tauri stars, TW Cam, EQ Cas, V360 Cyg, SS Gem, SU Gem, AC Her, EP Lyr, U Mon, TT Oph, TX Oph, UZ Oph, CT Ori, R Sct, R Sge, and RV Tau from the observed polarizations by removing the interstellar polarizations (Yoshioka (2000)[4], Yoshioka(2001)[5], Yoshioka (2002)[6], and Yoshioka(2003)[7]). We obtained the intrinsic polarizations for the other two stars, AD Aql and V Vul. We report the results for these stars in this paper.

Ⅱ. Observations and Reductions

The multi-channel polarimeter can measure liner polarizations simultaneously at 8 colors. These colors are indicated with the number of the channel in order of wavelength, whose effective wavelengths are 0.36, 0.42, 0.455, 0.53, 0.64, 0.69, 0.76, and 0.88 μm, respectively.

Using this polarimeter, we observed the degree of polarization p and the position angle of polarization θ. We also obtained the normalized Stokes parameters Q and U.

We obtained the intrinsic polarization from the observed polarization by removing the interstellar polarization. We adopted the empirical formula given by Whittet et al. (1992)[8] for a wavelength dependence of interstellar polarization p_{IS}, which is given as follows:

$$p_{IS}=p_{max}\cdot\exp[-K\cdot\ln^2(\lambda_{max}/\lambda)], \quad (1)$$

where p_{max} is the maximum degree of linear polarization which occurs at the wavelength λ_{max}; K is a linear function of λ_{max}:

$$\mathrm{K}=0.01+1.66\,\lambda_{max}. \quad (2)$$

The normalized Stokes parameters for the intrinsic polarization Q_* and U_* are calculated by the following equations:

$$Q_*=Q-p_{max}\cdot\exp[-\mathrm{K}\cdot\ln^2(\lambda_{max}/\lambda)]\cdot\cos2\theta_{IS}, \quad (3)$$

and $U_*=U-p_{max}\cdot\exp[-\mathrm{K}\cdot\ln^2(\lambda_{max}/\lambda)]\cdot\sin2\theta_{IS}$, (4)

where Q and U are observed quantities and θ_{IS} is the position angle of interstellar polarization. Then the intrinsic polarization

p_* and θ_* are calculated by the following equations:

$$p_*=\sqrt{Q_*^2+U_*^2}, \quad (5)$$

and $\theta_*=0.5\cdot\tan^{-1}(U_*/Q_*)$.

The p_{max}, λ_{max}, and θ_{IS} values are determined from stars near target stars which are thought to have no intrinsic polarization. We applied the modified near-neighbor method. The near-neighbor method is described by Bastien (1985)[9]. The modified near-neighbor method are described by Yoshioka (2000)[4]. The main modification point is that a distance is used as the parameter for obtaining p_{IS}, instead of E (B-V).

We used the interstellar polarization database compiled by Hirata (1999)[10], (hereafter referred to as ISPOL) as the catalogue of stars with no intrinsic polarization. The ISOPOL contains 13969 data for several wavelengths collected from 45 literatures.

Ⅲ. Results

The position, subclass, and distance for AD Aql and V Vul are given in **table 1**. The distance for AD Aql had not been determined. Thus, we have determined this distance from the relation between $\log_{10}P$ and $\log_{10}d-0.2m_V$ for the RV Tauri stars whose distances are determined, where P, d, and m_V are formal period (day), distance (pc), and apparent visual magnitude at mean brightness, respectively. The relation is shown in **figure 1**. The distance for AD Aql (P=65.4days and m_V=12.5) is determined from this relation.

The details of the results are as follows.

Table 1. Data on the RV Tauri Stars analyzed in this paper for Intrinsic Polarization. Periods are a formal period. The distance of V Vul is taken from Dawson (1979)[2], while that of AD Aql is determined by us as is described in the text. The sixth column gives the classification in the General Catalogue of Variable Stars (Kholopov et al. 1985)[14]. The seventh column gives the classification on the basis of optical spectra.

Star	α_{1950}	δ_{1950}	Period (day)	Distance (pc)	Variable Star	Optical Class Group
AD Aql	$18^h56^m25^s$	$-08°14'24''$	65.4	9770	RVa	B ?
V Vul	$20^h34^m27^s$	$+26°25'36''$	75.7	1930	RVa	A_1

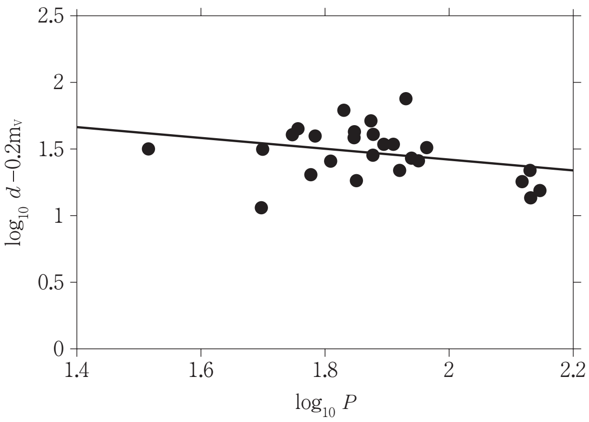

Fig.1 Relation between $\log_{10}P$ and $\log_{10}d-0.2m_V$ for the RV Tauri stars whose distances are determined. The solid line indicates the least-squares solution given by $\log_{10}d-0.2m_V=-0.41+2.24\log_{10}P$.

a) AD Aql

AD Aql belongs to the RVa group. According to Preston et al. (1963)[1], this star is classified as the group B with a question mark. According Giridhar et al.(1998)[11], this star is classified as the group B. They made an abundance analysis of this star, and obtained the result that it is very metal poor ([Fe/H]$=-2.1$) and its abundances of individual elements provide solid evidence of a photosphere ravaged by dust-gas separation.

AD Aql was observed once on 1996 April 2/3.

We found 16 stars from ISPOL database which are within 6° circle centered on AD Aql. We selected 10 stars (13 data) for the estimation of the θ_{IS} values among the above 16 stars whose θ values are determined. The selected 10 stars satisfy the conditions that their distances are larger than 600pc or their θ values are between 90° and 170°. We excluded the other stars because the θ values for these stars are outside of the general trend between θ value and distance, as is shown in **figure 2**. The estimated value is; $\theta_{IS}=148°$.

We selected 7 stars (7 data) for the estimation of $p_{IS}(B)$ value, where $p_{IS}(B)$ means the p_{IS} value for B color. The selected 7 stars satisfy the condition that their distances are larger than 200pc. We excluded the stars with distance smaller than 200pc, because the $p(B)$ values of these star show the dependence on distance which is different from that for the other stars, as is shown in **figure 3**. The estimated value is; $p_{IS}(B)=0.814\%$. We selected 4 stars (4 data) for the estimation of $p_{IS}(V)$ value, where $p_{IS}(V)$ means the p_{IS} value for V color. We excluded HD172275, because the $p(V)$ value of this star is too large (3.82%). The estimated value is; $p_{IS}(V)=0.991\%$. Assuming that $\lambda_{max}=0.50\,\mu$m, we determined that $p_{max}=0.91\%$ as the least-squares solution. We prescribed the λ_{max} value, because the least-squares solution gives unrealistic values for p_{max} and λ_{max} when not only p_{max} but also λ_{max} is taken as a free parameter.

The distances of the stars used for the determination of interstellar polarization are smaller than the distance of AD Aql. Thus, the accuracy of the θ_{IS} and p_{max} values seems to be rather low.

We obtained the intrinsic polarization by removing the interstellar polarization of our values. As is shown in **figure 4**, the $p*$ values show slightly a tendency to take a maximum at an intermediate wavelength (hereafter referred to as the 凸 type dependence), while the $\theta*$ values do not show a notable wavelength dependence.

b) V Vul

V Vul belongs to the RVa group and the A_1 group. V Vul was observed 5 times on 1993 October 24/25, 1993 October 27/28, 1993 November 28/29, 1994 December 24/25, and 1995 November 10/11.

We found 17 stars from ISPOL database which are within 6° circle centered on V Vul. We selected 10 stars (10 data) for the estimation of the θ_{IS} values among the above 17 stars whose θ values are determined. We excluded HD194525 and HD197702 because the θ values for these stars are too large, as is

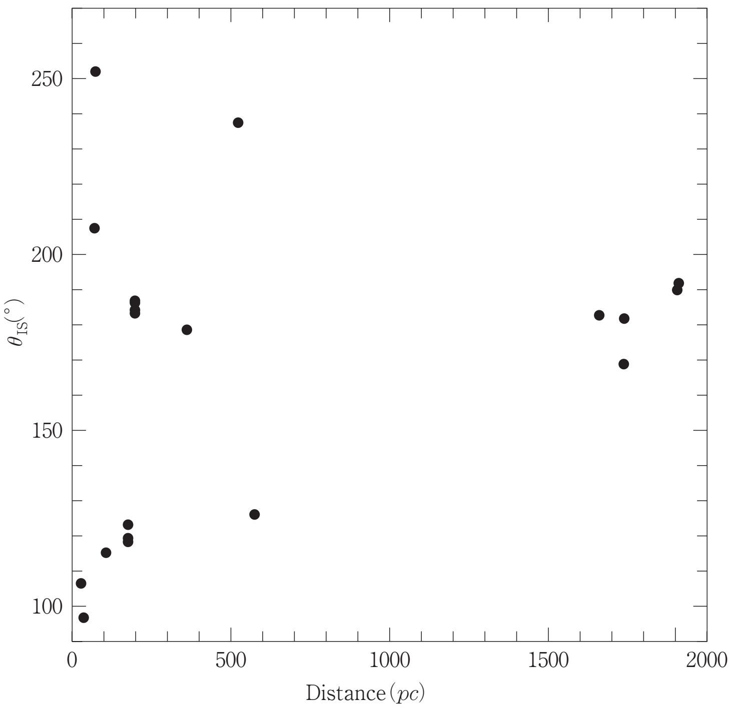

Fig.2 Dependence of the θ values near AD Aql on distance. For the θ values lower than 90°, 180° is added in order to keep the continuity of the variation in this graph.

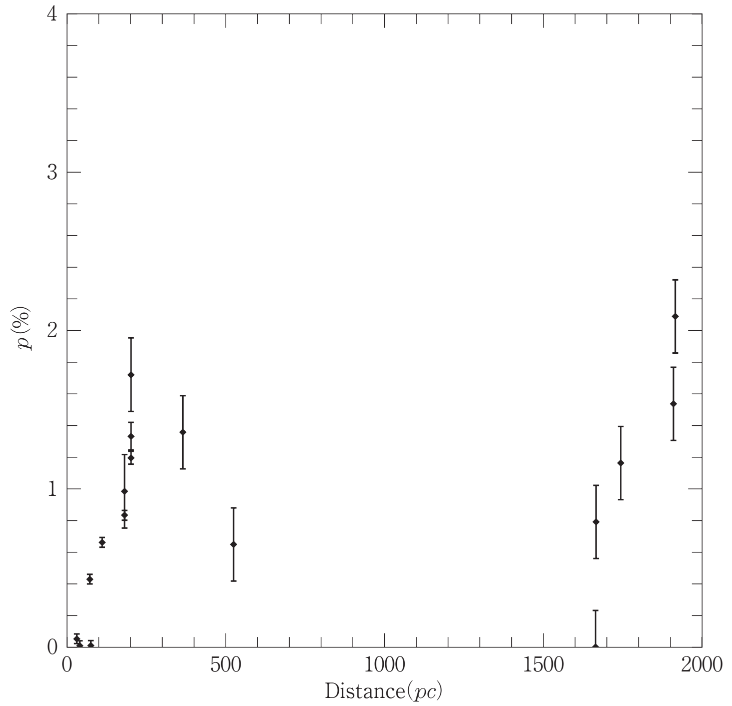

Fig.3 Dependence of the $p(B)$ values near AD Aql on distance.

shown in **figure 5.** The estimated value is; $\theta_{IS}=55^\circ$. In this estimation, the dependences of θ values on δ_{1950} and distance were taken into account.

We selected 12 stars (13 data) for the estimation of $p_{IS}(B)$ value. The estimated value is; $p_{IS}(B)=0.439\%$. In this estimation, the dependences of $p(B)$ values on α_{1950}, δ_{1950}, and distance were taken into account. We determined from the above $p_{IS}(B)$ value that $p_{max}=0.45\%$ and $\lambda_{max}=0.5\,\mu$m as the least-squares solution. In the above determination, we prescribed the λ_{max}

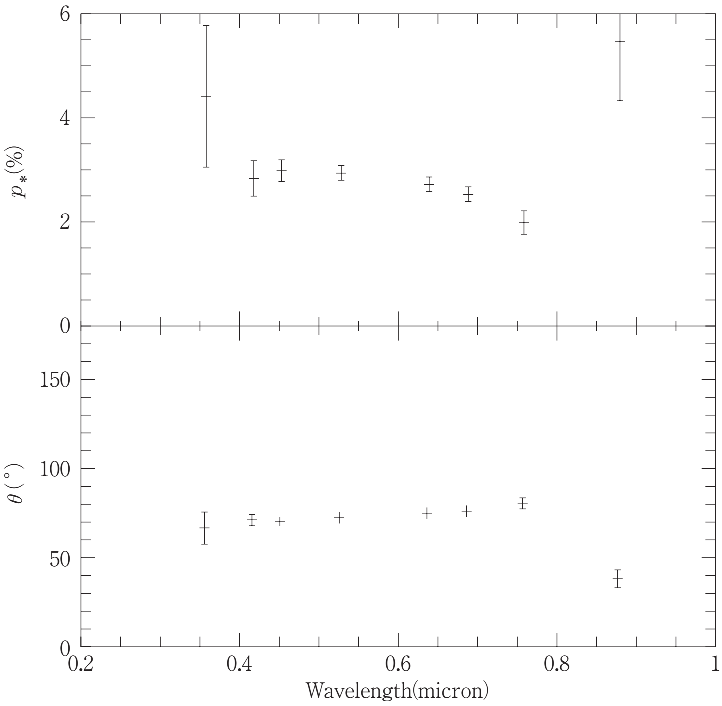

Fig.4 Wavelength dependence of the p_* and θ_* values of AD Aql on 1996 April 2/3.

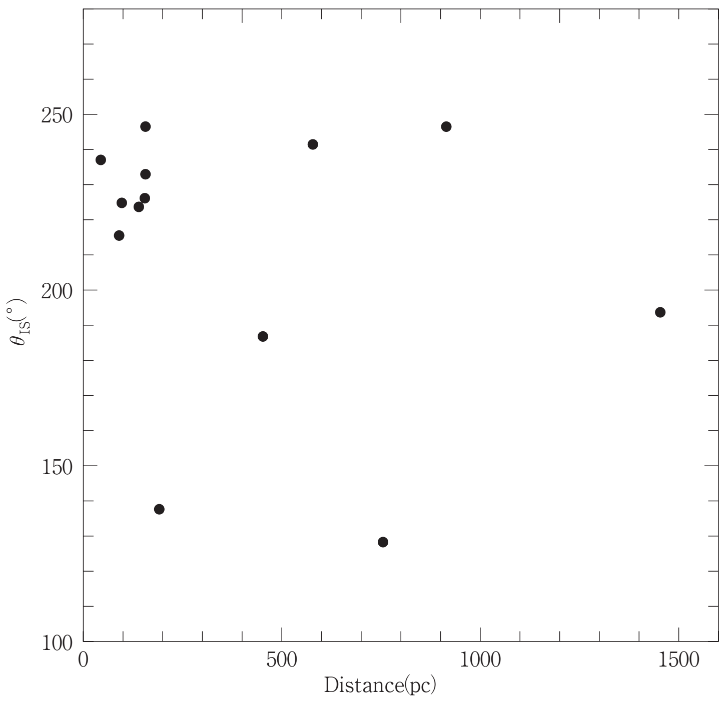

Fig.5 Dependence of the θ values near V Vul on distance. For the θ values lower than 100°, 180° is added in order to keep the continuity of the variation in this graph. The θ value of HD 194525 lies in the lower left part and that of HD 197702 lies in the lower right part.

value. We exclude $p_{IS}(V)$ for the determination of the p_{max} value, because we have only one data for $p_{IS}(V)$, and this $p_{IS}(V)$ value is too large (4.56%), as is shown in **figure 6.**

The distances of the stars used for the determination of interstellar polarization are smaller

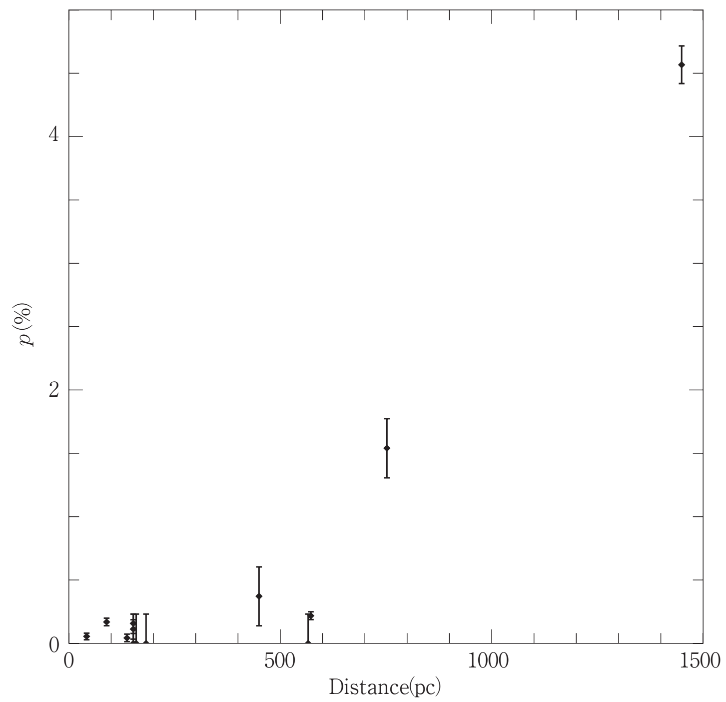

Fig.6 Dependence of the p values near V Vul on distance. The $p(V)$ value lie near the upper right corner.

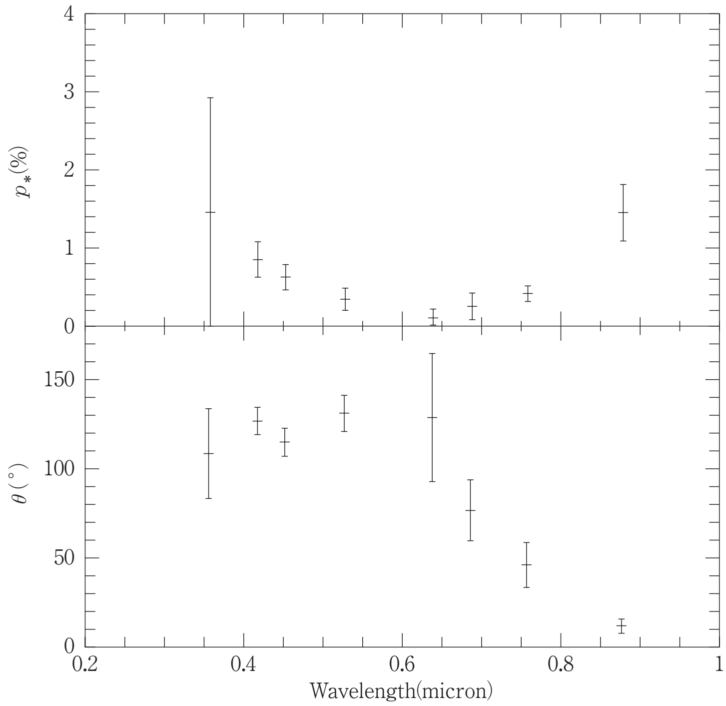

Fig.7 Wavelength dependence of the p_* and the θ_* values of V Vul on 1994 December 24/25.

than the distance of V Vul. Thus, the accuracy of the θ_{IS} and p_{max} values seems to be rather low.

We obtained the intrinsic polarization by removing the interstellar polarization of our values. The p_* values show various wavelength dependences. The values on 1994 December 24/25 show a tendency to take a minimum at an intermediate wavelength (hereafter referred to as the 凹 type dependence), as is shown in **figure 7**, while the values on 1995 November 10/11 decrease with wavelength, as is shown in **figure**

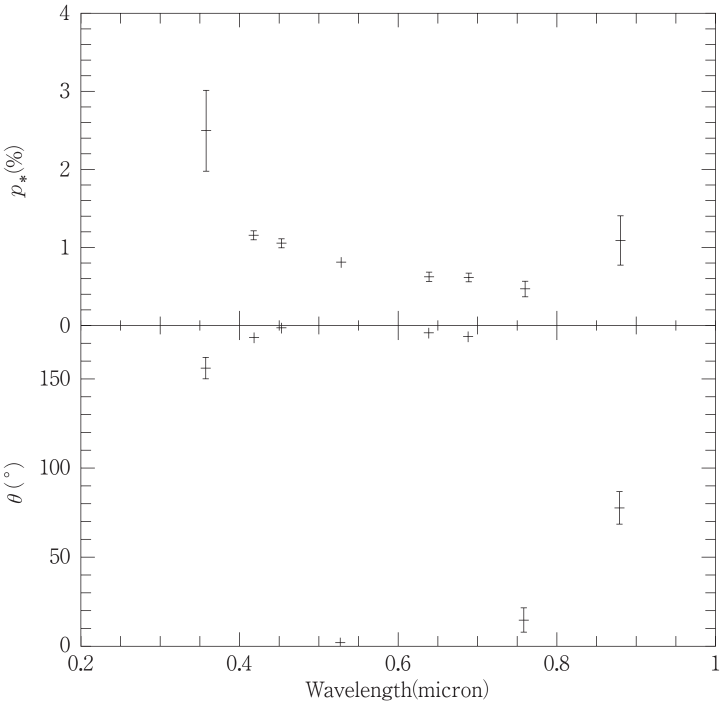

Fig.8 Wavelength dependence of the p_* and the θ_* values of V Vul on 1995 November 10/11.

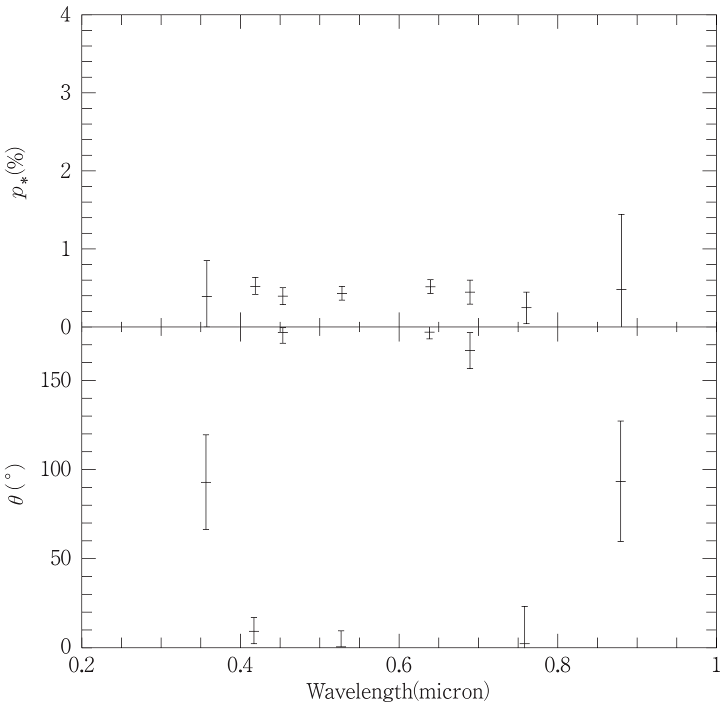

Fig.9 Wavelength dependence of the p_* and the θ_* values of V Vul on 1993 October 24/25.

8. On the other hand, the other values do not show a notable wavelength dependence, as is shown in **figure 9.** The θ_* values do not show a notable wavelength dependence.

Ⅳ. General Features of Intrinsic Polarization

We have obtained the intrinsic polarizations of all the RV Tauri stars observed with the multi-channel

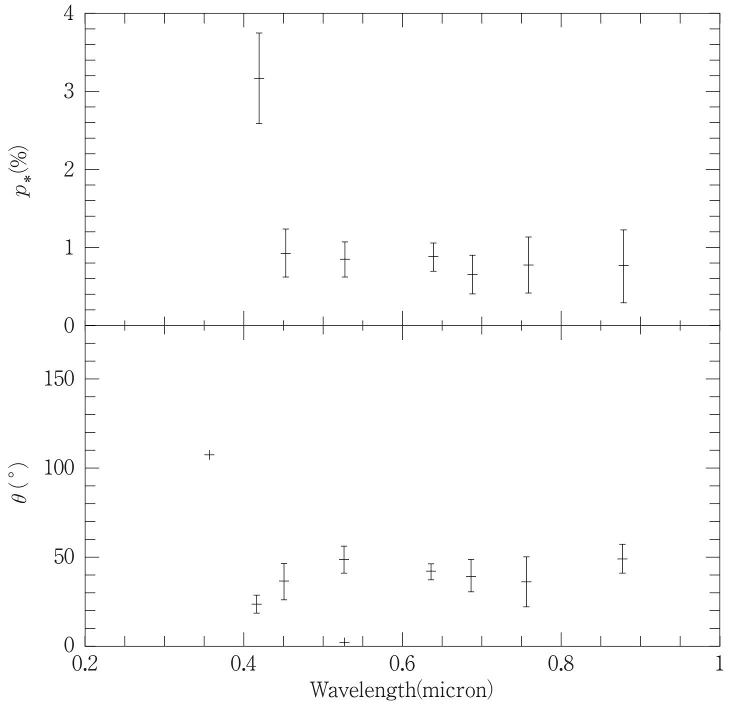

Fig.10 Wavelength dependence of the $p*$ and the $\theta*$ values of V360 Cyg on 1995 November 9/10.

polarimeter at the Dodaira Station. Though the errors of the $p_{\max}$ values for some of the stars are large, the following general features of intrinsic polarization can be derived.

1) Both of the group A stars and the group B stars show various types of wavelength dependence of $p*$ values. That is, some of them show the 凸 type dependence and some of them show the 凹 type dependence. The $p*$ values for some of them decrease with wavelength and those for some of them increase with wavelength. Some of them show dependences at different phases. However, except for CT Ori the group B stars do not show the 凸 type dependence. On the other hand, the only C group star observed by us, V360 Cyg, does not show a notable wavelength dependence, as is shown in **figure 10**.

2) Generally, the $\theta*$ values do not show a notable wavelength dependence. In case they show a wavelength dependence, there is a tendency that the $p*$ values also show a wavelength dependence.

3) The $p*$ values do not always take larger values at light minima. But there is a tendency that the $p*$ values take a maximum or a minimum value at primary light mimima and that the $p*$ values show a wavelength dependence at primary light minima which is different from that at the other phase. They especially tend to decrease with wavelength at primary light minima.

We can interpret the above features as follows.

1) The feature 1) indicates that the intrinsic polarization changes according to a phase change in CDE and/or according to a phase change in energy distribution of a photosphere. Especially, the time variation in the wavelength dependence of $\theta*$ values indicates the change in the geometric arrangement of CDE. The time variation in the wavelength dependence of $p*$ values indicates the change in the size distribution of the grain of CDE. Especially, the 凹 type dependence indicates that there are two CDE's which have different grain size distributions. The group B stars have a tendency to take the 凹 type dependence and, except for CT Ori, most group B stars do not show the 凸 type dependence. Thus, the group B stars seem to have a tendency to have two CDE's with different grain size distributions. In fact, on the basis of multiwavelength photometric observations Shenton et al. (1992)[12] suggested the presence of at least two distinct CDE's for AC Her belonging to the group B. Furthermore, on the basis of infrared observation with 10m Keck I reflector, Jura et al. (2000)[13] found an edge-on dust ring around AC Her and they concluded that the ring has two types of grain with size of less than 0.1 μm and with size of more than 200 μ m. If these grains scatter the optical radiation from the photosphere of AC Her, we will observe the intrinsic polarization whose $p*$ values

have two peaks one of which ranges at a wavelength shorter than optical region and the other ranges at a wavelength far longer than optical region. Thus, we will observe the wavelength dependence of p_* values which were observed for AC Her. Concerning CT Ori, the only B group star which show the 凸 type dependence of p_* values, the formal period is rather large (135.5days) and this star is not definitely classified as RV Tauri star in the General Catalogue of Variable Stars (Kholopov et al. (1985)[14]. Furthermore, according to Dawson (1979)[2], the mean DDO colors suggest that CT Ori is a giant star, and according to Momiyama (2003)[15], the spectra of CT Ori indicate that this star is a subgiant or a dwarf. Thus there is the possibility that none of the B group stars show the 凸 type dependence of p_* values. Concerning V360 Cyg, the only C group star observed by us, the accuracy of the p_{max} value obtained by us seems to be rather low, as is described in Yoshioka (2002)[6]. Thus, there is a possibility that the true p_{max} value is larger than our value and the intrinsic polarization of this star is nearly zero, which suggest that the C group star has no conspicuous CDE.

2) The feature 2) indicates that generally CDE's do not change in a geometrical arrangement. Furthermore, it indicates that the wavelength dependence of θ_* values is caused by the variation in the size distribution of grain.

3) The feature 3) indicates that the variation of intrinsic polarization is caused by the variation in the radiation from the photosphere or by that the variation of CDE's is linked with the brightness variation.

The right or wrong of the above interpretations depends on which is the origin of the intrinsic polarization, CDE or photosphere. We are now observing RV Tauri Stars with HBS (Henko Bunko Sokkousochi), which will elucidate the origin.

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