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Long-Term Periodic Variations in Polarization of Three RV Tauri Stars, SU Gem, U Mon, and RV Tau

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3個のおうし座RV型星，ふたご座SU星，いっかくじゅう座U星，おうし座RV星の偏光の長周期変動

吉　岡　一　男

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脈動変光星である．この変光星は，光度変化をもとに，RVa型とRVb型に細分類されており，RVb型は脈動周期の光度変化に重なって長周期の光度変化が見られるのに対して，RVa型ではそのような長周期変化は見られない．

われわれは，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，この星の多色偏光測光観測を行っている．

その結果，現在までに観測された17個のおうし座RV型星の中で，ふたご座SU星，いっかくじゅう座U星，おうし座RV星の3個の星で，偏光が長周期の時間変動をしていることを検出した．これら3個の星はすべてRVb型である．そして，観測された偏光の長周期時間変動は周期的で，その周期は長周期光度変化の周期と大体一致しているようである．この長周期の時間変動はおうし座RV星のほうが，いっかくじゅう座U星よりも顕著である．一方，観測誤差が大きいので，ふたご座SU星に対しては，長周期時間変動の大きさについては，明確な結論は下せない．さらに，偏光の長周期時間変動の特徴から判断すると，RVb現象の説明の1つとして提案されてる星周圏ダスト殻を伴う伴星による単純な掩蔽によっては，この時間変動が引き起こされてはいないようである．

ABSTRACT

The RV Tauri stars are semiregular variables whose light curves are characterized by alternate deep and shallow minima. On the basis of light curves the RV Tauri stars are divided into the RVa group and the RVb group. The RVa group is characterized by a relatively regular light curve, while the RVb group is characterized by a superimposition of a long-term variation.

The author has been making the multicolor polarimetric observations of RV Tauri stars, using the 91cm reflector with the multi-channel polarimeter at the Dodaira Station of the National Astronomical Observatory.

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Among 17 stars observed to date, showed three stars, SU Gem, U Mon, and RV Tau, long-term time variations of polarization. All these stars belong to the RVb group, and the periods of the long-term variations of polarization seem to be close to the long-term brightness periods. The long-term variation of polarization for RV Tau is more conspicuous than that for U Mon, while a definite conclusion cannot be obtained for SU Gem due to a large observational scatter. Furthermore, it seems that the long-term variation of polarization is not caused by the simple eclipse by a comparison star with a circumstellar dust shell, which has been suggested as one of the explanations for the RVb phenomenon.

1. Introduction

The RV Tauri stars are semiregular variables which lie between the Cepheids and the Mira-type variables in the HR diagram. Their light curves are characterized by alternative deep and shallow minima. The periods between two adjacent deep minima, which are called the double or formal periods, range from 30 to 150 days. The RV Tauri stars have relatively regular periods, but the magnitudes of maxima and minima are not constant. Interchanges of minima sometimes occur, i.e., two deep or two shallow minima occur in succession.

On the basis of light curves the RV Tauri stars are divided into 2 subgroups, RVa and RVb. The RVa group is characterized by a relatively regular light curve, and the interchanges of minima do not occur frequently. The RVb group is characterized by a rather irregular light curve, especially by a superimposition of a long-term brightness variation.

The RV Tauri stars generally thought as radial pulsators, but some investigators assert that they also perform a non-radial pulsations. The presence of the primary and secondary minima is theoretically interpreted in two ways. Kovacs and Buchler (1988)[1] have proposed that the double minima is a result of low dimensional chaos, while Takeuti and Petersen (1983)[2] have proposed that it is a result of an integer resonance 2:1 between the fundamental mode and the first overtone. The observations seem to support the resonance hypothesis.

The RV Tauri stars show strong excess infrared radiations, 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) objects 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 has been making the multicolor polarimetric observations of 17 RV

Tauri stars since 1993 October 23, using the multi-channel polarimeter attached to the 91cm reflector at the Dodaira Station of the National Astronomical Observatory. The long-term time variations of polarization were detected for some of the stars in these observations. In this papar, we report the results concerning these time variations, which were obtained from the observations between 1993 October 23 and 1998 February 12.

2. Observations

The multi-channel polarimeter can measure linear 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 0.88μm, respectively. The construction and the operation of this polarimeter are described by Kikuchi (1988)[4]. An accuracy of better than 0.03% can be obtained for bright stars with this polarimeter. The method of reduction is described by Yoshioka (1994)[5] and Yoshioka (1995)[6].

3. Results

3.1. Time Variations of Polarization

We detected time variations of polarization for many of the stars observed in this study. The results are summarized in table 1. In this table, Confirmed Stars are the stars whose time variations for many channels are larger than 3σ; Possible Stars are the stars which show the time variations but the ranges of variation are smaller than 3σ; Undetected Stars are the stars whose time variations are not detected; Unknown Stars are the stars which were observed only once or the stars which were observed more than 2 times but the observational errors are too large to draw a significant conclusion. Furthermore, the stars also are included in the Confirmed Stars whose time variations have been detected by other observers or whose polarizations observed by other observers differ from our results by more than 3σ, even if our observations do not show the time variations.

Table 1 indicates that many RV Tauri stars show the time variations of polarization. Out of 17 stars, 7 stars are the Confirmed Stars and 3 stars are the Possible Stars. There is only one star, SS Gem, that has confirmedly found to show no time variation. Therefore, most RV Tauri stars may show the time variations. As the time variations of observed polarization mean that the stars observed have intrinsic polarizations, most RV Tauri stars may have intrinsic polarizations. This result seems to be reasonable, because the RV Tauri stars have CDE's.

Table 1. Results as to the time variation of polarization. The classification in the General Catalogue of Variable Stars (Kholopov et al. 1985)[7] is given in perentheses.

Confirmed Stars	TW Cam (RVb)	SU Gem (RVb)	AC Her (RVa)
	U Mon (RVb)	R Sct (RVa)	RV Tau (RVb)
	V Vul (RVa)		
Possible Stars	V360 Cyg (RVa)	TT Oph (RVa)	R Sge (RVb)
Undetected Stars	SS Gem (RVa)		
Unknown Stars	AD Aql (RVa)	EQ Cas (RVa)	EP Lyr (RVb)
	TX Oph (RVa)	UZ Oph (RVa)	CT Ori (RV)

3.2. Long-Term Periodic Variations of Polarization

Out of 7 Confirmed Stars in table 1, 3 stars show conspicuous time variations. These stars are SU Gem, U Mon, and RV Tau. All of these stars belong to the RVb group. In the following, the details of the time variations are described separately for these stars.

a) SU Gem

According to the General Catalogue of Variable Stars (Kholopov et al. (1985)[7], hereafter referred to as GCVS), the formal period of SU Gem is 50.12 days and the period of the long-term brightness variation (hereafter referred to as the long-term brightness period) of this star is 690days. SU Gem was observed 9 times on 1993 December 24/25, 1993 December 26/27, 1993 December 27/28, 1994 March 29/30, 1995 December 12/13, 1997 January 28/29, 1997 February 26/27, 1997 December 10/11, and 1997 December 11/12.

Since the average apparent visual magnitude of this star is larger than +12, as is shown in figure 1, the observational errors were generally large. However, as is shown in figure 2, the time variations larger than the observational errors were detected for this star. In this figure, the observed polarizations for the channel 4 (0.53μm) are plotted with the normalized Stokes parameter Q as abscissa against the normalized Stokes parameter U as ordinates. Large time variations were also detected for the other channels.

Figure 3 shows a time variation of U values in the channel 3 (0.455μm). In this figure, the two observations on 1993 December 26/27 and 1997 December 11/12 are excluded because of large observational errors. A solid line indicates the least-squares solution which is given by the following expression:

$$U=4.04 \cos\left[2\pi\ (t-50432)/690\right]-0.19, \qquad (1)$$

which is obtained on condition that the period is 690days. The solid line agrees fairly well with the observational values, which suggests that the time variation

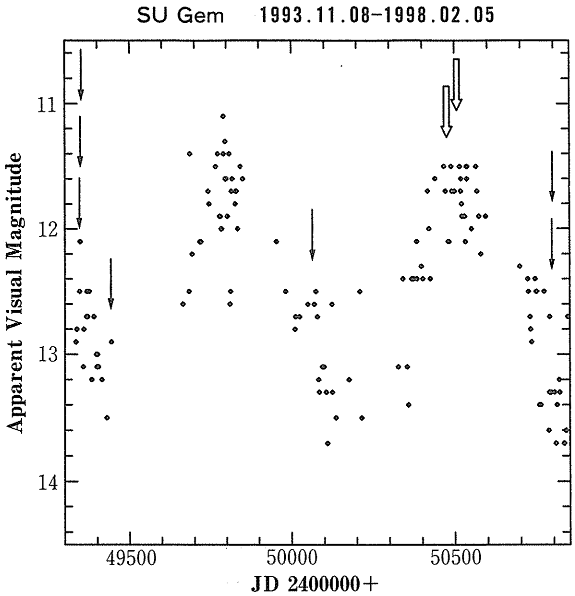

Fig.1. Light curve of SU Gem during our observations, where the plotted data are given by VSOLJ. The arrows indicate the dates of our observations. The open arrows indicate the dates at which the maximum U values were observed.

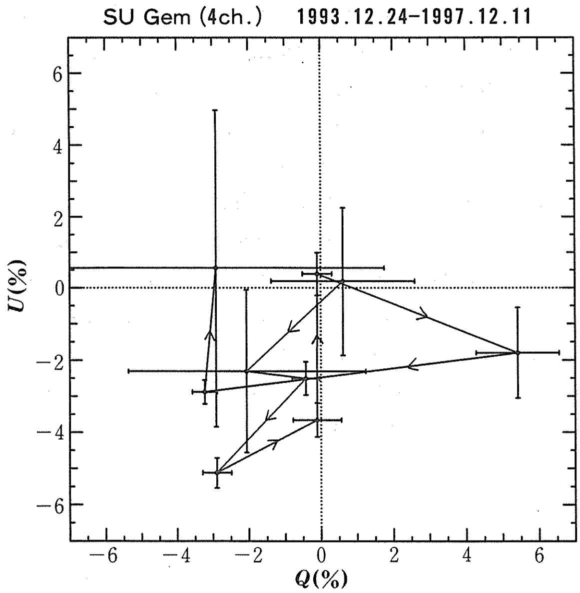

Fig.2. Time variation of the observed polarization of SU Gem for the channel 4 in the QU plane.

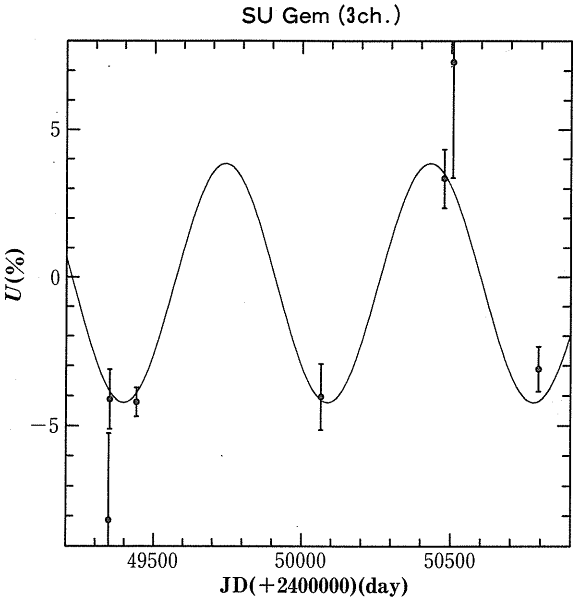

Fig.3. Time variation of the observed U values of SU Gem for the channel 3.

of polarization is a periodic change with the long-term brightness period.

Furthermore, as is shown in figures 1 and 3, only maximum values for U were observed during a period of long-term maximum brightness. The phases of the formal period for the two observational dates with the maximum U values differ each other. The phase on 1997 January 28/29, i.e., corresponds to that slightly before primary light minimum, while the phase on 1997 February 26/27 corresponds to that during brightening which is similar to the phase on 1994 March 29/30 when U took a minimum value. The similar results were obtained for the other channels and for Q values. These results also suggest that the polarization changes with the long-term brightness period and that the long-term variation dominates the short-term variation with the formal period.

The semiamplitude of the long-term variation in Q values which is obtained on condition that the period is 690days varies between 1.0% and 4.1%, depending on the channels of the polarimeter. The semiamplitude, however, has no clear correlation with wavelength. On the other hand, the semiamplitude for U values has a tendency to decrease with wavelength. For example, the semiamplitude for the channel 2 (0.42μm) is 7.1%, while that for the channel 7 (0.76μm) is 1.4%.

The wavelength dependence of the degree of linear polarization p for SU Gem had changed between 1995 December 12/13 and 1997 December 10/11. The p values before 1995 December 12/13 take a maximum at an intermediate wave-

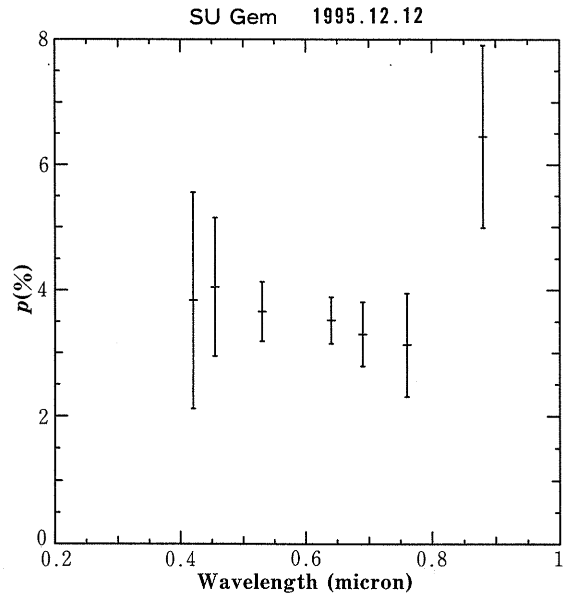

Fig.4. Wavelength dependence of the Observed p values of SU Gem on 1995 December 12/13.

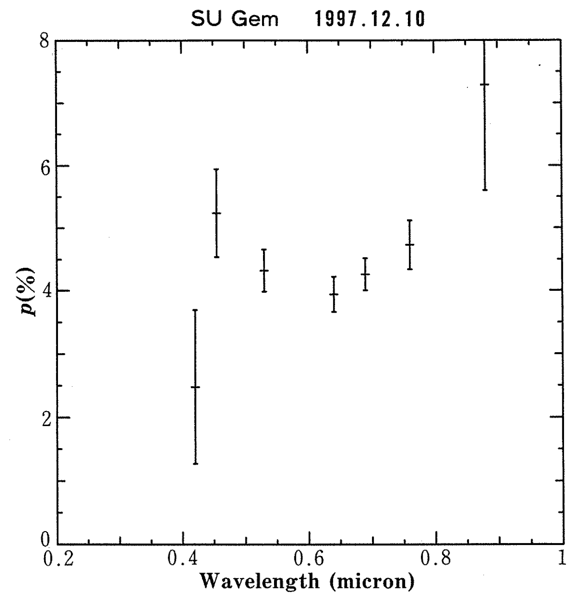

Fig.5. Wavelength dependence of the Observed p values of SU Gem on 1997 December 10/11.

length, as is shown in figure 4, while the p values after 1997 December 10/11 take a minimum at an intermediate wavelength, as is shown in figure 5. The relation between the above change in the wavelength dependence and the phase of the formal period or of the long-term brightness period is not clear.

b) U Mon

According to GCVS, the formal period of U Mon is 92.26days and the long-term brightness period is 2320days. This value of long-term brightness period was derived by Loreta (1939)[8]. Percy (1991)[9] derived 2475days as the long-term brightness period from the observations by the American Association of Variable Star Observers. The long-term time variation of U Mon was also derived from observations of radial velocity, though the period of long-term time variation of radial velocity (hereafter referred to as the long-term velocity period) differs according to observers. For example, Sanford (1933)[10] found that the center-of-mass as seasonally determined varies with a period of about 2300days. Abt (1955)[11] derived 1980days or 2640days as the long-term velocity period from a comparison with the data by Sanford (1933)[10], depending on whether 4 or 3 cycles had elapsed since Sanford's observations. On the other hand, Preston (1964)[12] derived 1500days or 3000days from a comparison with the data by Abt (1955)[11], depending on whether 2 or 1 cycles had elapsed since Abt's observations. Preston (1964)[12] also derived 1560days, taking the data by Sanford (1933)[10] also into account, and he suggested 1560 days is the most probable period among the above three values. Furthermore, Pollard and Cottrell (1995)[13] derived 2597days on the basis of the radial velocities observed at the Mount John University Observatory.

U Mon was observed 20 times on 1993 October 27/28, 1993 November 27/28, 1993 December 25/26, 1994 February 2/3, 1994 February 23/24, 1994 March 31/April 1, 1994 April 4/5, 1994 December 24/25, 1995 January 15/16, 1995 March 20/21, 1995 December 8/9, 1995 Dwcember 12/13, 1996 January 31/February 1, 1996 February 2/3, 1996 February 27/28, 1996 November 25/26, 1997 January 27/28, 1997 December 10/11, 1997 December 11/12, and 1998 February 10/11.

U Mon has been observed polarimetrically by Shakhovskoi (1964)[14], Aliev (1965)[15], Serkowski (1970)[16], Wolf (1972)[17], and Nook et al. (1990)[18]. Serkowski (1970)[16] and Nook et al. (1990)[18] yielded also intrinsic polarizations for U Mon from their observations by removing an interstellar polarization which were determined by Serkowski (1970)[16] on the assumptions that an intrinsic polarization in *B* band is the same as in *V* band and its value is equal to the average of the observed polarization in the above two bands. Aliev (1965)[15], Serkowski (1970)[16], and Nook et al. (1990)[18] detected the time variation of polarization with the formal period. Furthermore, Nook et al. (1990)[18] found that their values of position angle of polarization θ for the intrinsic polarizations are systematically smaller than those by Serkowski (1970)[16] by up to 30°, which indicates that the intrinsic polarization undergoes a long-term time variation. Nook et al. (1990)[18] suggested that the long-term time variation may be due to a slow rotation in the scattering plane of the CDE around U Mon, since U Mon is a long-period binary with an unseen companion which could change the geometry of the CDE.

Our observation shows the time variation of polarization with the formal period, too. Moreover, our observation also shows a long-term time variation of polarization. Figure 6 shows a time variation of Q values in the channel 4. A solid line indicates the least-squares solution which is given by the following expression:

$$Q=-0.30\cos\left[2\pi\ (t-50382)/2640\right]+1.77, \qquad (2)$$

which is obtained on condition that the period is 2640days. Similar time variations of Q values were observed for the other channels. Figure 7 shows a time variation of U values in the channel 3. A solid line indicates the least-squares solution which is given by the following expression:

$$U=0.82\cos\left[2\pi\ (t-50186)/2640\right]+0.24, \qquad (3)$$

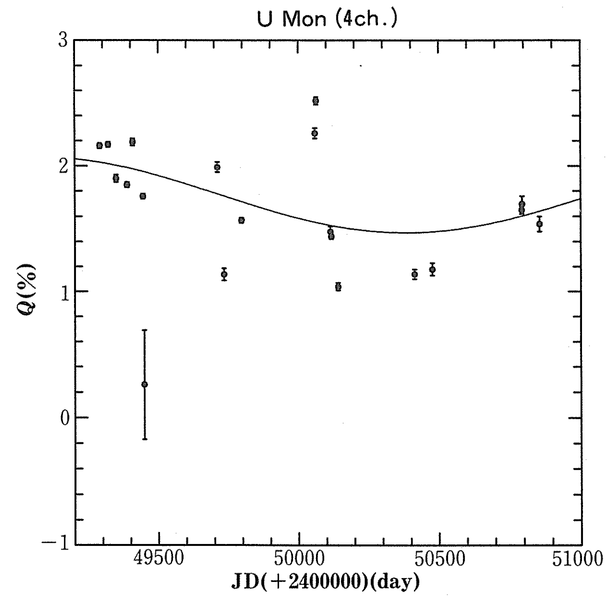

Fig.6. Time variation of the observed Q values of U Mon for the channel 4. The solid line indicates the least-squares solution given by $Q=-0.30\cos[2\pi\ (t-50382)/2640]+1.77$, which is obtained on condition that the period is 2640days.

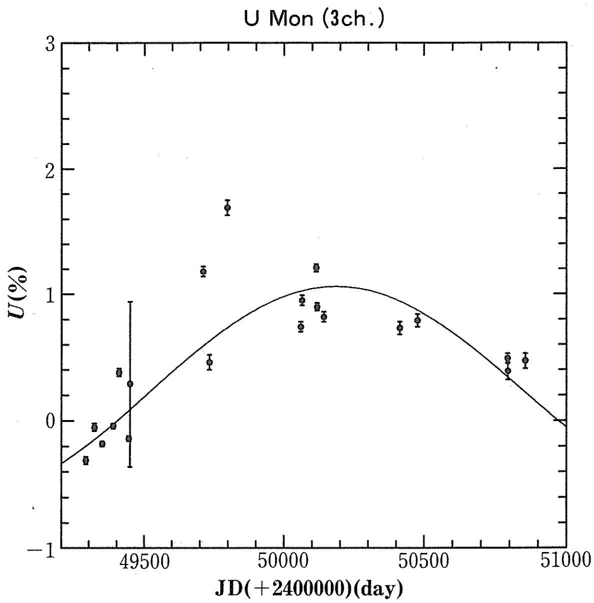

Fig.7. Time variation of the observed U values of *U* Mon for the channel 3. The solid line indicates the least-squares solution given by $U=0.82\cos[2\pi(t-50186)/2640]+0.24$, which is obtained on condition that the period is 2640days.

which is obtained on condition that the period is 2640days. Similar time variations of *U* values were observed for the other channels, though the semiamplitudes for the channels 2, 3, and 4 are about 0.8% and they are larger than those of about 0.6% for the channels 5,6, and 7.

As is shown in figure 6, the long-term time variation is not clear for *Q* values, because the time variation with the formal period is large. However, figure 7 shows clearly the long-term time variation for *U* values, and it seems possible that the long-term variation is periodic with a period of 2640days. Among the long-term brightness periods and the long-term velocity periods cited above gives the period of 2640days the least-squares solution with the smallest standard deviation for *U* values between the channel 3 and the channel 5. This period also gives the least-squares solution with the smallest standard deviation for *Q* values of the channel 4, though the periods of 2597days and of 1980 days give the smallest standard deviations for *Q* values of the channels 3 and 5, respectively. There is, anyway, no appreciable differnce in the standard deviation among the above periods which are equal to or larger than 1980days.

On the other hand, the periods of 2475days or of 2597days give the smallest standard deviations, when other observations also are taken into account. For example, Serkowski (1970)[16] and Wolf (1972)[17] observed in *V* band, and Nook et al. (1990)[18] observed at 0.5361μm with intermediate-band width. Figure 8 shows a time variation of U values in the channal 4, where their observations are added to our observation, together with those of shakhovskoi (1964)[14] whose detector was an antimony-cesium photocathode without filters. A solid line indicates the least-squares solution which is given by the following expression:

$$U=0.65 \cos [2\pi (t-50151)/2475]+0.29. \quad (4)$$

In this case, the period of 2475days gives the smallest standard deviation. This period also gives the smallest one for Q values, though scattering is larger than that for U values. Furthermore, Wolf (1972)[17] observed also at B band whose effective wavelength is 0.428μm and at 0.638μm with intermediate-band width, which correspond to those of the channels 2 and 5, respectively. When the observations by Wolf (1972)[17] are added, the periods of 2597 days and of 2475 days give the smallest standard deviations in the channel 2 for Q and U values, respectively. On the other hand, the periods of 1980days and of 2597days give the smallest standard deviations in the channels 5 for Q and U values, respectively. Finally, Nook et al. (1990)[18] also observed at 0.6877μm with intermediate-band width, which corresponds to that of the channel 6. When the

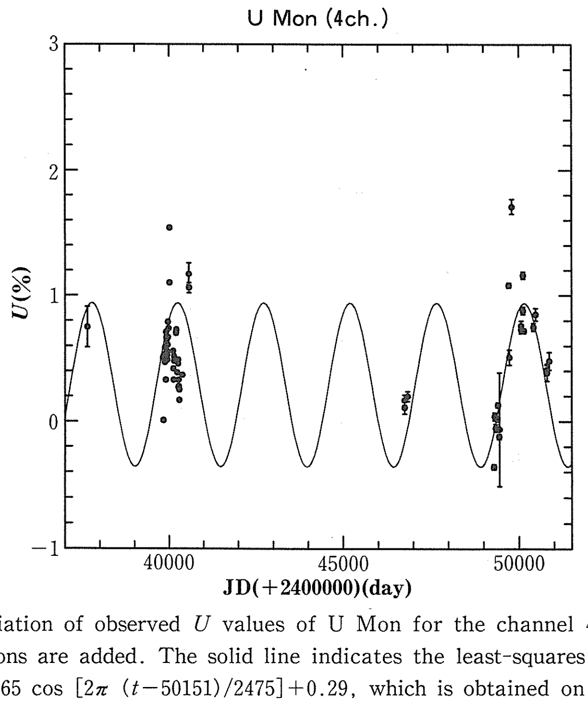

Fig.8. Time variation of observed U values of U Mon for the channel 4, where other observations are added. The solid line indicates the least-squares solution given by $U=0.65 \cos [2\pi (t-50151)/2475]+0.29$, which is obtained on condition that the period is 2475days.

observations by Nook et al. (1990)[18] are added, the periods of 2475days and of 2597days give the smallest standard deviations in the channel 6 for Q and U valeus, respectively.

c) RV Tau

According to GCVS, the formal period of RV Tau is 78.70days and the long-term brightness period is 1224days. Zsoldos (1996)[19] made a period analysis using visual observations done between 1980 and 1995, and he derived 78.57days and 1168days as the formal and the long-term brightness period, respectively. He also found that there is a drastic decrease in the amplitude of the long-term brightness variation, while the amplitude of the formal period is practically the same. The amplitude of the long-term brightness variation between 1980 and 1995, i.e., is $0^m.21$, while that between 1925 and 1940 is $0^m.61$. On the other hand, the formal period and the long-term brightness period show only slight variations, which values between 1925 and 1940 are 78.42days and 1190days, respectively. Zsoldos (1996)[19] guessed that the change had occured rather abruptly around the early 1940's.

RV Tau was observed 19 times on 1993 October 23/24, 1993 October 27/28, 1993 November 27/28, 1993 December 22/23, 1993 December 23/24, 1994 February 2/3, 1994 February 19/20, 1994 February 23/24, 1994 December 21/22, 1995 January 15/16, 1995 January 18/19, 1995 December 8/9, 1995 December 12/13, 1996 February 28/29, 1996 November 27/28, 1997 January 28/29, 1997 December 10/11, 1998 February 9/10, and 1998 February 10/11.

Our observation clearly shows a long-term time variation of polarization, though the time variation of polarization with the formal period is not cospicuous. Figure 9 shows the time variation of polarization in the channel 4 for RV Tau in the QU plane. The period of our observation is 1571days and it is longer than the long-term brightness period of 1168days or 1224days. As is shown in this figure, the data points turn clockwise more than one revolution round a trajectory which is nearly decribed as circle. This figure suggests that the long-term variation of polarization is a periodic one with a period of the long-term brightness period. This is also indicated in figures 10 and 11. Figure 10 shows a time variation of Q values in the channel 5. A solid line indicates the least-squares solution which is given by the following expression:

$$Q=-0.60 \cos [2\pi (t-50465)/1224]+2.01, \quad (5)$$

which is obtained on condition that the period is 1224days. Figure 11 shows a time variation of U values in the channel 5. A solid line indicates the least-squares solution which is given by the following expression:

$$U=2.50 \cos [2\pi (t-50733)/1168]+1.23, \quad (6)$$

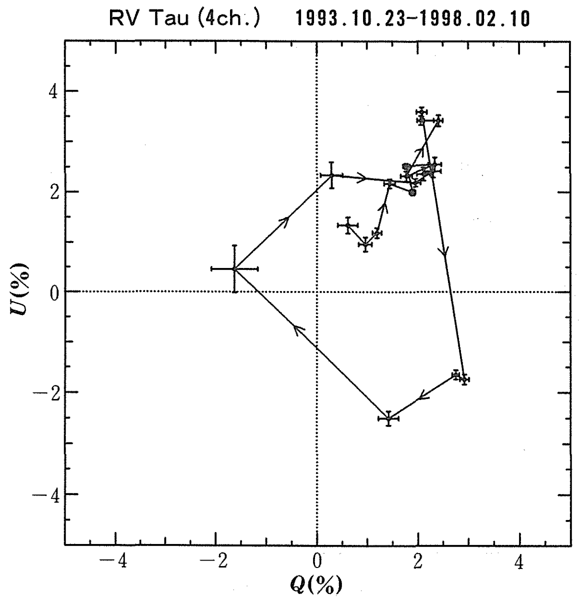

Fig.9. Time variation of the observed polarization of RV Tau for the channel 4 in the *QU* plane.

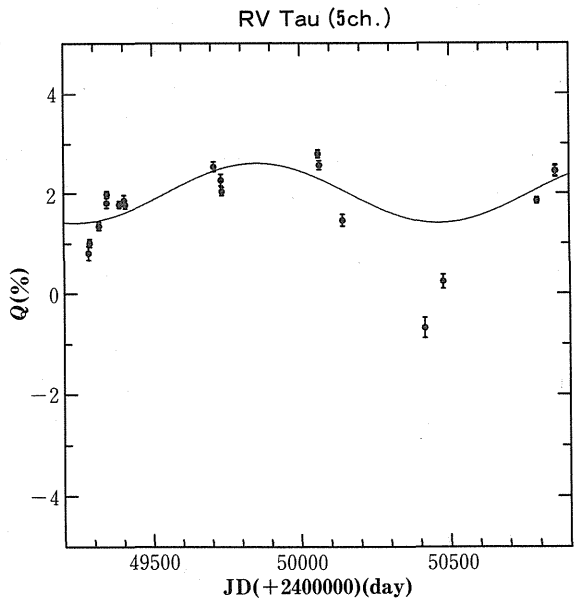

Fig.10. Time variation of the observed Q values of RV Tau for the channel 5. The solid line indicates the least-squares solution given by $Q=-0.60\cos[2\pi(t-50465)/1224]+2.01$, which is obtained on condition that the period is 1224days.

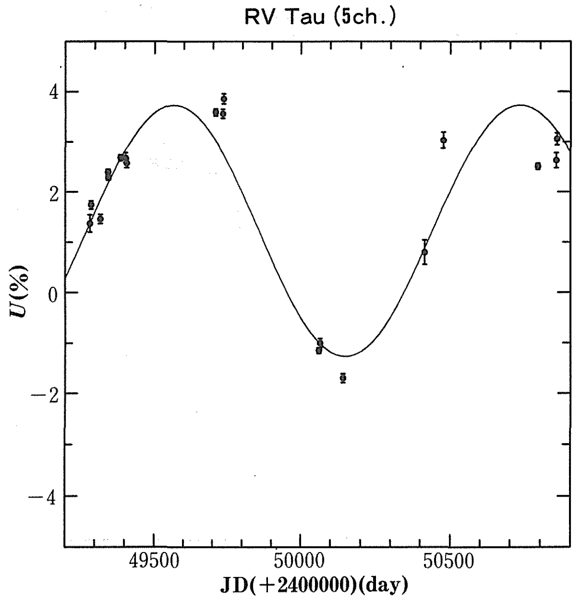

Fig.11. Time variation of the observed U values of RV Tau for the channel 5. The solid line indicates the least-squares solution given by $U=2.50 \cos [2\pi\ (t-50733)/1168]+1.23$, which is obtained on condition that the period is 1168days.

which is obtained on condition that the period is 1168days. As is shown in these figures, the Q and U values, especially the U values, vary with a period of about the long-term brightness period. Between the period of 1168days and 1224 days gives the period of 1224days the least-squares solution with a slightly smaller standard deviation for the Q values, while the period of 1168days gives the one with smaller standard deviation for the U values. The semiamplitudes for the Q values are about 0.6% and they hardly depend on the wavelength, while the semiamplitudes for the U values decrease with the wavelength from 3.7% for the channel 2 to 2.2% for the channel 7.

Figure 12 shows a visual light curve of RV Tau during our observations, where the plotted data are given by the Variable Star Observers League of Japan (hereafter referred to as VSOLJ). As is shown in this figure, the period during which Q values were positive and U values were negative, i.e., between JD 2450060 and JD 2450142, corresponds to the phase in the long-term brightness variation during darkening and slightly before minimum. During this period, the degree of linear polarization p decrease with wavelength, as is shown in figure 13, while p values do not show such a dependence on wavelength during the other periods, as is shown in figure 14.

The polarization of RV Tau does not show a clear time variation with the

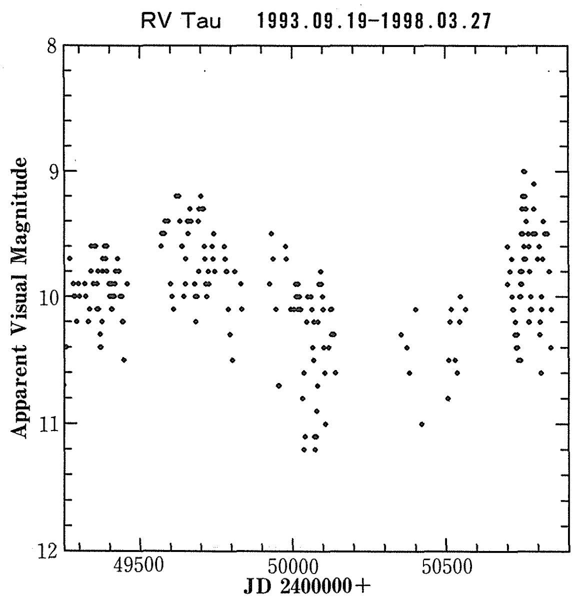

Fig.12. Light curve of RV Tau during our observations, where the plotted data are given by VSOLJ.

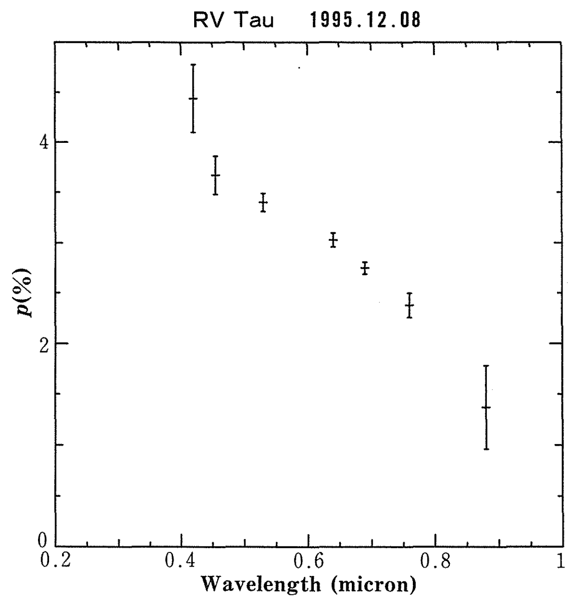

Fig.13. Wavelength dependence of the Observed p values of RV Tau on 1995 December 8/9.

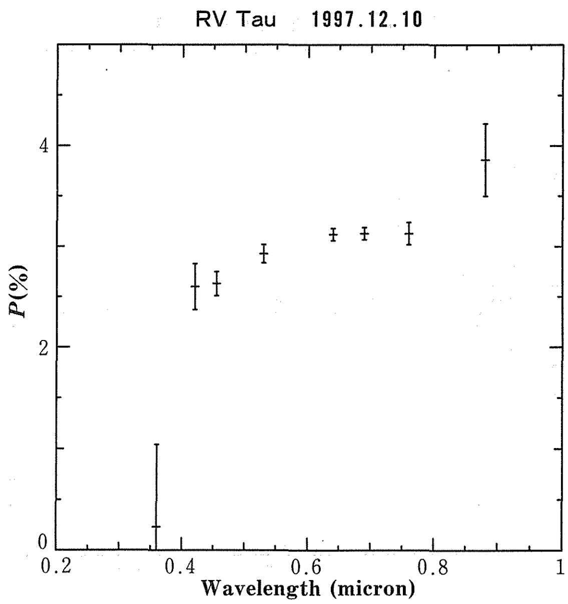

Fig.14. Wavelength dependence of the Observed p values of RV Tau on 1997 December 10/11.

formal period. For example, both Q and U values were positive on 1993 October 23/24, while Q values were positive and U values were negative on 1996 February 28/29. The phases of the first and the second observation correspond to that during darkening to the primary light mimimum and that shortly after the secondary light maximum or during darkening to the primary light mimimum, respectively. Thus, their polarizations differ entirely, though their phase in the formal period are similar.

4. Discussion

We detected the long-term time variations of polarization for the RV Tauri stars of the RVb group, SU Gem, U Mon, and RV Tau, as well as the short-term time variations with a formal period. We have for the first time found that these long-term variations are periodic ones with about the long-term brightness periods.

This suggest that the long-term variations of polarization are caused by the same mechanism that causes the RVb phenomenon. This suggestion is supported by the result that the long-term variations of polarization are distinct for the above three stars which show clearly the RVb phenomenon.

At present, the RVb phenomenon is explained in two ways. One explanation interprets it as a result of binarity, while the other one interprets it as a phenomenon caused by an outer layer of a single star. A simple binary explanation assumes that a companion star has a circumstellar dust shell where we see an orbital plane nearly from edge-on and a darkening occurs when a RV Tauri star is eclipsed by the circumstellar dust shell. The simple binary explanation is difficult to explain the following features of the long-term variations of polarization.

1) The long-term variations seem to be quasi-periodic.

2) The periods of the long-term variations of polarization seem to be nearly equal to the long-term brightness periods, while the polarization generally varies with one half of the period of revolution when it is observed from edge-on.

3) As is shown in figure 9, the trajectory of time variation in QU plane for RV Tau is nearly circular, while it is nearly linear when we see a orbital plane from edge-on.

Therefore, it seems that the long-term variation of polarization is not caused by the simple eclipse by the companion star with a circumstellar dust shell, though the explanation such as the one by Wealkens and Waters (1993)[20] where the RVb phenomenon is caused by a periodic eclipse by a circumbinary dust-torus is possible.

Further data analysis is being made for the other RVb type stars in order to study the long-term variation of polarization.

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