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CCD photometry of a δ Scuti variable in an open cluster

III. V 465 Persei in the α Persei cluster

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Abstract. We present the results of real-time CCD differential photometry for the δ Scuti variable V 465 Per. The observations were performed for thirteen nights between November, 1994 and January, 1995. Total 3345 points of differential V magnitudes were collected during the observation period of 76.4 hours. From the Fourier analysis, we have detected four frequencies as follows; f_1=14.040 c/d, f_2=17.208 c/d, f_3=33.259 c/d and f_4=13.721 c/d. Two frequencies of 12.50 c/d and 33.49 c/d detected previously by Slovak (1978, ApJ 223, 192) may correspond to our f_1 and f_3, respectively. For each frequency, pulsation constants of $Q_1 = 0.0520 \pm 0.008$, $Q_2 = 0.0425 \pm 0.006$, $Q_3 = 0.0220 \pm 0.003$ and $Q_4 = 0.0533 \pm 0.008$ were derived from several observational properties of V 465 Per. Only the value of Q_3 is found to be within the range of theoretical p-mode oscillations and the other ones show large differences relative to the theoretical values. The high Q-values might be interpreted as the occurrence of g-mode oscillations in V 465 Per, even though it can not rule out the possibility of systematic errors (Breger 1990; Delta Scuti Star Newsletter, 2, 13) related to rotational velocity.

Key words: stars: individual: V 465 Per — stars: oscillations — stars: δ Sct

1. Introduction

This is the third paper in a series performing the real-time CCD differential photometry of δ Scuti variable stars in open clusters at the Seoul National University Observatory(SNUO). In the first paper (Kim & Lee 1996, – Paper I), V650 Tau in the Pleiades cluster was studied. The observational results of BT Cnc in the Praesepe cluster was presented in the second one (Kim & Lee 1995, – Paper II). The main purposes of this long-term observational project are as follows. First, we perform CCD photometry of δ Scuti variable stars showing complicated light curves. They have multiple pulsation periods so as to be one of the most important observing targets of *asteroseismology* (Brown & Gilliland 1994). For this work, accurate data sets should be obtained over a sufficiently long-time baseline. From the observed data, we detect precisely their pulsation periods as many as possible and identify the pulsation mode for each period. Second, comparing our observational results with the previous one, we investigate the variations of pulsation period and its amplitude (for reviews, see Breger 1990a and Rodríguez et al. 1995).

There are several advantages to observe variable stars in open clusters using a CCD camera. First, it allows more chances to find comparison stars near the variable stars. Second, we can get more accurate data because a number of objects are observed simultaneously in the same CCD frame. It is also possible to produce well-defined differential magnitudes even under non-photometric nights and at a less-photometric site like a university campus (Kreidl 1993). Finally, we are able to compare the physical properties (pulsation mode, mass, radius and age, etc.) derived from the pulsation model with ones obtained from the other methods such as the evolutionary model, because the physical properties of open clusters are known well.

In order to investigate the incidence of δ Scuti stars in the α Persei cluster, Slovak (1978) carried out the differential photometry for 24 A∼F type stars in or near the δ Scuti instability strip. He detected three variable stars as follows; V 459 Per (=BD +48°894, H 501), V 461 Per (=BD +48°905, H 606), V 465 Per (=BD +47°842, H 906). Among these, V 465 Per is the bluest and the largest-amplitude variable, displaying complicated light curves. From the data obtained on two nights, he found a dominant pulsation period of 1.92 hours and the secondary period of 43 minutes. Its membership was confirmed by the combined astrometric, photometric and spectroscopic

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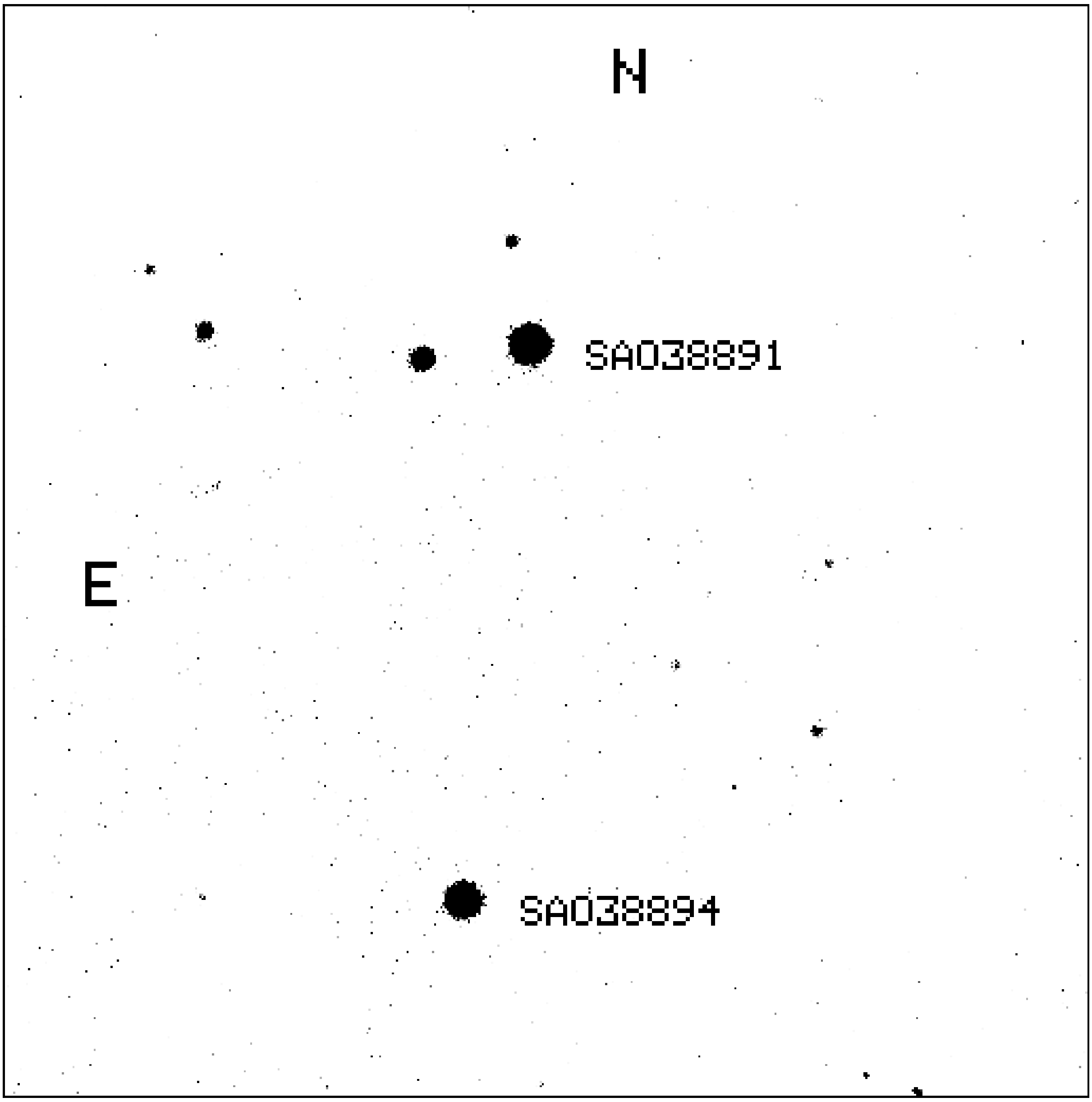

Fig. 1. Observed CCD field ($8\overset{'}{.}1 \times 8\overset{'}{.}1$) near V 465 Per (=SAO 38891). A comparison star (SAO 38894) and a faint check star located at the east of the variable star were monitored simultaneously

results (Prosser 1992). The present paper provides observational results of V 465 Per ($V = 8\overset{m}{.}78$, A6Vn) obtained during the period between November, 1994 and January, 1995. The observation and data reduction are reported in Sect. 2. The frequency analysis and the identification of pulsation modes are presented in Sect. 3 and Sect. 4, respectively.

2. Observation and data reduction

V 465 Per was observed at the SNUO with a photometrics PM512 CCD camera and Johnson V filter mounted on the the 61 cm Ritchey-Chrétien telescope. The CCD chip has an area of 516×516 pixels and a pixel size of 20 μm. The size of the field of view in the CCD image is $8\overset{'}{.}1 \times 8\overset{'}{.}1$ (0.945 electrons pixel^{-1}; Sung 1995) at the f/7 Cassegrain focus of our telescope. We used the 4X gain factor of which the gain is 4.11 electrons ADU^{-1} and the readout noise is 6.2 electrons.

The observations were carried out for thirteen nights (76.4 hours observation) from November 21, 1994 to January 17, 1995. The exposure time and the duty cycle were 35 s and 80 s, respectively. The photometric seeing (FWHM) was typically $4\overset{''}{.}5$ during the observing run. Evening twilight flat field frames were obtained for each night to flatten the raw CCD frames. Real-time

aperture photometry was performed with the *SNUCCD* program (Kim et al. 1993), adopting a somewhat large aper-
ture size of 20 pixels. The observational techniques and the methods of data reduction are the same as Papers I and II.

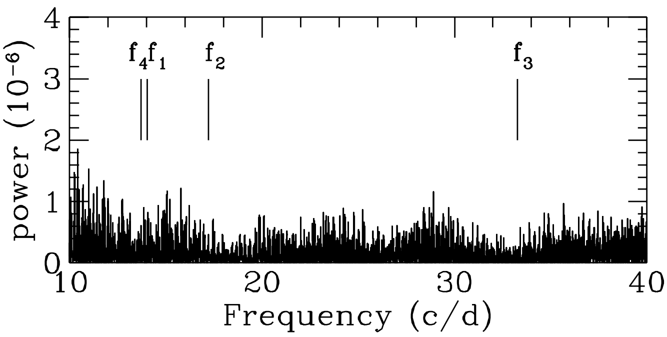

Fig. 2. Power spectra of differential magnitudes for a faint check star. It seems to be only noisy powers originated in the observation errors. Four frequencies (f_1, f_2, f_3 and f_4) of V 465 per identified in this paper are also shown for comparison

An observed CCD field near V 465 Per (= SAO 38891) is shown in Fig. 1. We used SAO 38894 ($V = 8\overset{m}{.}9$) as a comparison star considering its brightness. A faint check star near (east) the variable star was also monitored. No peculiarity of the comparison star was observed during the observing run and the constancy of its brightness was confirmed by the power spectrum of magnitude differences between the check and comparison stars (Fig. 2). Since the above three stars were observed simultaneously in the same CCD frame, differential magnitudes could be obtained independently from atmospheric variations.

Light curves of V 465 Per are shown in Fig. 3, where the points denote the differential magnitudes observed for thirteen nights. The data were corrected for the atmospheric extinction and normalized by subtracting the mean of differential magnitudes for each night in order to correct the long-term instrumental drift. These data are available in electronic form from the first author or from the WWW (World Wide Web) addressed of *http://www.boao.re.kr/∼slkim/works.html*. The solid curves represent the analytic light curves computed with four frequencies obtained in the present study.

3. Frequency analysis

It is somewhat difficult to resolve multiple pulsation frequencies from complicated light curves. Particularly, prewhitening procedure extracting step by step each *real* frequency in the power spectrum should be done carefully. We performed the frequency analysis using a package of computer programs, which utilize DFT (Discrete Fourier Transform) and multiple linear least square fitting method. The sinusoidal variation corresponding to the previously identified frequencies is subtracted from the original time-domain data, similar to PERIOD program used by the Breger group (for example, Breger et al. 1994) and the sequential CLEANest algorithm (Foster 1995). The detailed prewhitening methods and period searching techniques were given in Paper II.

The power spectra of V 465 Per are shown in Fig. 4. The spectral window in the first panel shows strong side bands, particularly at 1 cycle/day which is produced by the daily gaps of observation. After the successive prewhitening of each frequency peak, four frequencies are identified in the next four panels as follows; $f_1 = 14.040$ c/d, $f_2 = 17.208$ c/d, $f_3 = 33.259$ c/d, $f_4 = 13.721$ c/d. The observational results of V 465 Per are summarized in Table 1. The fourth frequency which has a smaller value of signal to noise amplitude ratio (S/N) than the criterion of 4.0 (Breger et al. 1993) might be uncertain. In the last panel, the power spectrum of the data after subtraction of four frequencies shows some additional peaks, probably caused by the observation noise.

Slovak (1978) detected two pulsation period of V 465 Per. A period of 1.92 hours (= 12.50 c/d) was shown in his light curves obtained from two nights of observations and the secondary period of 43 minutes (= 33.49 c/d) was detected using a frequency analysis. The first frequency having the most dominant pulsation amplitude may correspond to our f_1 and the second frequency is similar to our f_3. The other two frequencies (f_2 and f_4) detected in this study might not be found in his result due to his limited data sets.

4. Pulsation mode identification

One of the main problems concerning the interpretation of observed frequencies is to identify their pulsation modes. The most reliable method for pulsation mode identification is to analyze the profile variations of a high-resolution spectral line (for example, Kennelly et al. 1992). With the use of photometric data, the pulsation mode can be identified from the phase difference and amplitude ratio of color variations (Watson 1988; Garrido et al. 1990). In the case of small light variations such as V 465 Per, however, it would be difficult to obtain the color variations with sufficient accuracy. We used only the sizes and ratios of observed frequencies in order to identify the pulsation modes of V 465 Per.

The pulsation mode for each observed frequency can be identified from the comparison between the theoretical pulsation constant and observational one derived from the photometric parameters (Breger 1990b). The pulsation constant Q is expressed in terms of four observable parameters as follows (Breger et al. 1993);

$$\log Q = -6.456 + \log P + 0.5 \log g + 0.1 M_{\rm bol} + \log T_{\rm eff}. \quad (1)$$

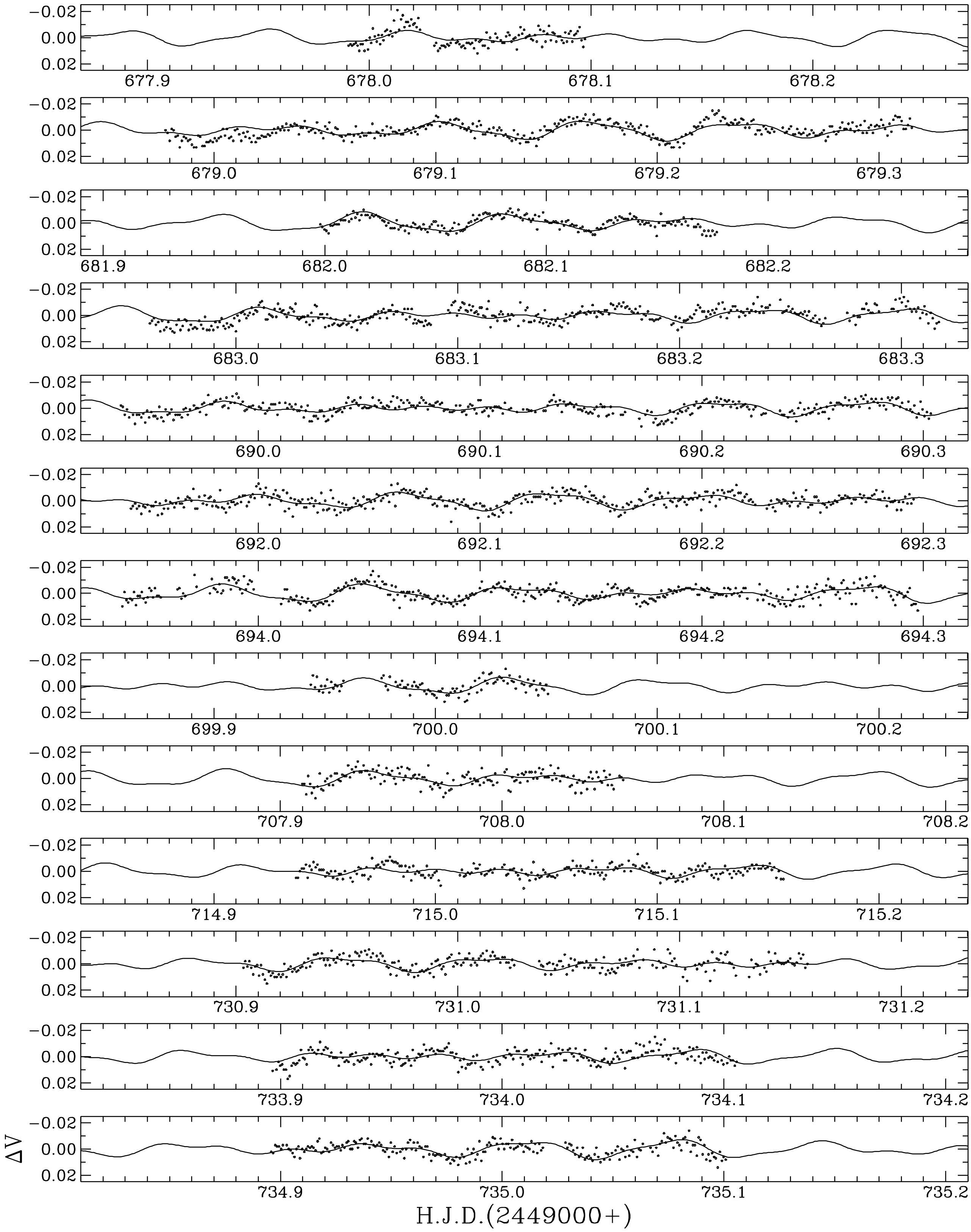

Fig. 3. Light curves of V 465 Per. The points denote the actual data observed for thirteen nights and the fitting lines represent the analytic light curves computed with four frequencies detected in this study

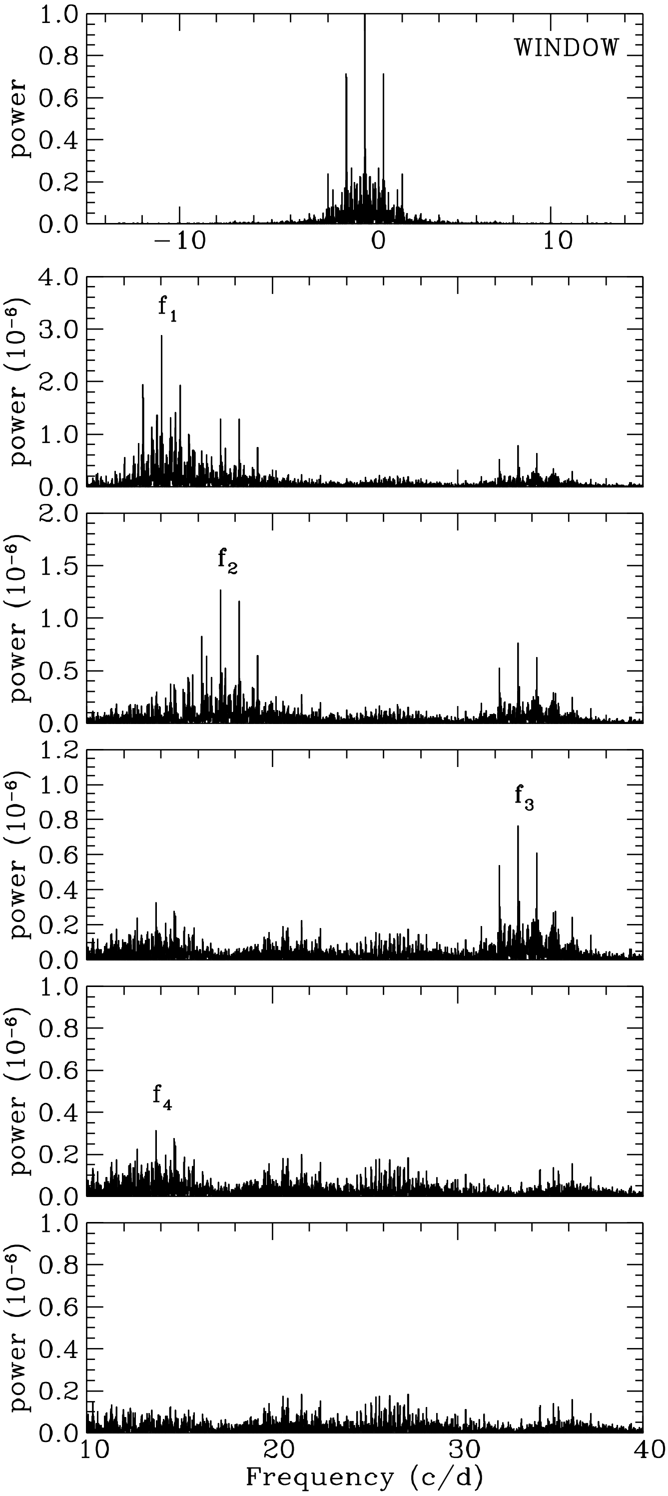

Fig. 4. Power spectra of V 465 Per observed between November, 1994 and January, 1995. The spectral window is shown in the top panel. Four frequencies can be identified in the next four panels

For V 465 Per, we adopted the values of log $T_{\rm eff}$ = 3.928 and log g = 4.312 (López de Coca et al. 1990) which were derived from the *uvby*, Hβ photometry. The absolute magnitude of $M_{\rm bol} = 2.36 \pm 0.16$ was calculated from the distance modulus of $(m - M)_0 = 6.10 \pm 0.16$ and interstellar reddening of $E(V - I) = 0.16$ for the α Per cluster (Stauffer et al. 1989), and the bolometric correction of -0.02. The $\delta m_1 = 0.002$ (García et al. 1995) indicates the normal solar abundance. The effective temperature and the absolute magnitude are similar to the another values, log $T_{\rm eff}$ = 3.918 derived from the *UBV* photometry ($B-V = 0.276$; Prosser 1992) and $M_V = 2.34$ estimated from the *uvby*, Hβ photometry (López de Coca et al. 1990).

The pulsation constants for the four frequencies are obtained by the above equation as follows; $Q_1 = 0\overset{\rm d}{.}0520 \pm 0.008$, $Q_2 = 0\overset{\rm d}{.}0425 \pm 0.006$, $Q_3 = 0\overset{\rm d}{.}0220 \pm 0.003$ and $Q_4 = 0\overset{\rm d}{.}0533 \pm 0.008$. The uncertainties were estimated from the error of photometric parameters, following the method by Breger (1990b). Comparing these Q-values with the theoretical ones, only the value of Q_3 exists within the range of p-mode oscillations (for example, $Q \leq 0.035$; Dziembowski & Pamyatnykh 1991). The other values fall within the range of g-mode oscillations which are not common among the δ Scuti variable stars; Breger & Beichbuchner (1996) argued that the low-frequency variations reported in several δ Scuti variables might be caused by variable comparison stars and/or instrumental/atmospheric effects. So far, four candidates of BI CMi, 44 Tau, CE Oct and IK Peg (Breger & Beichbuchner 1996), 63 Her (Mangeney et al. 1991; Breger et al. 1994) and IFA star 9 in NGC 6134 (Frandsen et al. 1996) may be known as δ Scuti variables with low-frequency (g-mode) oscillations.

In order to obtain the information on the pulsation mode, we investigate the frequency ratios of V 465 Per. The ratios of two frequencies, f_1/f_2=0.816 and f_1/f_3=0.517 are similar to those given by theoretical frequency ratios of two radial modes, P_2/P_1=0.810 and P_3/P_0=0.521 (Breger 1979), respectively. To match the results of frequency ratios with ones of pulsation constants, the observational parameters of V 465 Per should decrease to the value predicted at the theoretical p-mode oscillations, as the same case of HD 18878 (Mantegazza & Poretti 1993) and BI CMi (Mantegazza & Poretti 1994). If f_1 is the first overtone radial mode (1H-mode; P_1) or the fundamental radial mode (F-mode; P_0), the value of log Q should be decreased by the amount of about -0.318 or -0.197, respectively. This difference of log Q may be too large to be interpreted as errors of photometric parameters.

In conclusion, we have detected four pulsation frequencies in V 465 Per. Among these, deduced from the high Q-values, three frequencies (including two dominant frequencies of $f_1 = 14.040$ c/d and $f_2 = 17.208$ c/d) may be associated with g-mode oscillations. This is very important because g-mode oscillations are able to provide the

Table 1. Observational results of V 465 Per

This study (Nov. 1994 ∼ Jan. 1995)						Slovak (1978)
Frequency		Q ($\times 10^{-2}$)	$A_j^\dagger$	$S/N^\ddagger$	$\phi_j^\dagger$	Frequency
$f_1 = 14.040$ c/d	162.5 μHz	5.20[d]	$3.5 \pm .1$ mmag	11.8	$-0.14 \pm .03$	12.50 c/d
$f_2 = 17.208$	199.2	4.25	$2.3 \pm .1$	7.8	$+2.05 \pm .04$	—
$f_3 = 33.259$	384.9	2.20	$1.7 \pm .1$	6.1	$+1.93 \pm .06$	33.49
$f_4 = 13.721$	158.8	5.33	$1.1 \pm .1$	3.9	$+3.55 \pm .09$	—
	Residuals		4.14 mmag			

†: $V = V_0 + \Sigma_j\ A_j \cos\{2\pi f_j(t - t_0) + \phi_j\}$, $\quad t_0 = \mathrm{H.J.D.}\,2449000$
‡: S/N = (power for each frequency/mean power in the range of 10 ∼ 40 c/d after prewhitening of all frequencies)$^{1/2}$.

information on the inner part of stars such as the extent of the convective overshooting (Dziembowski & Pamyatnykh 1991). However, it is noted that the Q-value might be affected by systematic error related to rotational velocity (Breger 1990b; Pérez Hernández et al. 1995). Therefore the pulsation mode identification on the basis of the Q value may involve some uncertainty for a fast rotator such as V 465 Per which has a rotational velocity, $v \sin i = 150$ km s^{-1} (López de Coca et al. 1990). For V 465 Per, extensive observations by a multisite campaign would be required to detect more pulsation frequencies and to investigate the pulsational characteristics such as g-mode oscillations.

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