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A CCD Photometric Study of Close Binary V445 Cep

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We present new *BVR* CCD photometric light curves for the close binary star V445 Cep. A new photometric solution and absolute physical dimensions of the system were derived by applying the Wilson-Devinney program to our observed light curves and radial velocity curves published by Pych et al. The evolutional status of V445 Cep was found to coincide with those of the general low mass ratio contact binary systems.

Keywords: *BVR* CCD observation, WD solution, low mass ratio contact binary

1. INTRODUCTION

The light variation of V445 Cep (BD +71°1109, HD 210431) was discovered by the Hipparcos mission (European Space Agency 1997). The amplitude of Hipparcos light curve is in the magnitude range of 0.03. Duerbeck (1997) and Rucinski (2002) reported that the light variation of V445 Cep may be caused by the pulsation because the color index of V445 Cep is abnormally bluer compared to the period-color relation of contact binaries. However, Pych et al. (2004) reported that V445 Cep is an eclipsing binary with very low mass ratio (q = 0.17 ± 0.01) and mass function of ($[M_1 + M_2] \sin^3 i = 0.134 \pm 0.006 M_\odot$) based on their radial velocity curve. They expected that it would be difficult to determine the orbital elements of V445 Cep because the amplitudes of the radial velocity curve and the light curve are very small as a contact binary. Grenier et al. (1999) classified the spectral type of V445 Cep as A2V based on their low dispersion spectroscopic observation and found the binary system velocity is Vo = 38.6 ± 9.6 km/sec. These results are confirmed by Pych et al. (2004) who determined that the spectral type of V445 Cep is A2V, and the binary system velocity is Vo = 40.69 ± 0.95 km/sec. Tycho-2 Catalogue (Hog et al. 2000) presented that the spectral type of V445 Cep is A4 based on the color index of B-V = 0.123.

The Hipparcos light curve was made without filter and the orbital elements of the star have not been presented yet. Thus we carried out CCD photometric observations to obtain the complete *BVR* light curves of V445 Cep. Then we have analyzed our multicolor light curves and radial velocity curves published by Pych et al. (2004) for the photometric and spectroscopic solutions of V445 Cep. Finally we have compared our results with the characteristics of a category of the contact binary stars which show low mass ratios (Lee et al. 2006, Oh et al. 2004, 2005, 2009) to investigate whether V445 Cep belongs to the category.

2. CCD PHOTOMETRIC OBSERVATION

BVR CCD photometric observations of V445 Cep have been carried out for 8 days at the Mt. Sobeak Observatory with a 61 cm telescope (f/13.5) and the electrically-cooled Finger Lakes Instrumentation 2 K CCD camera. The *BVR* filters were used with the effective wavelength similar to those of Johnson Photometry. Using the cus-

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tomary image reduction and analysis facility (IRAF) package, we processed the frames to correct the bias level and the pixel-to-pixel inhomogeneities of the quantum efficiency and applied simple aperture photometry to get instrumental magnitudes. The observation points are 298 (B), 297 (V), and 305 (R), respectively. Table 1 lists the properties of V445 Cep, comparison star and check star provided by SIMBAD Astronomical Data Base.

The orbital phases were calculated using the light elements of Pych et al. (2004) and the magnitude difference (Δm) were obtained using comparison star listed in Table 1. The standard deviations of the magnitude difference between the comparison stars and check stars are used as observational errors which are $\pm0.^{m}007$, $\pm0.^{m}009$, and $\pm0.^{m}008$ for B, V, and R, respectively. Fig. 1 shows the *BVR* light curve of V445 Cep. We obtained two times of minima of the primary eclipse determined by the method of Kwee et al. (1956) and list them with their standard deviations in Table 2.

Table 1. Physical properties of V455 Cep, comparison, and check stars.

Parameter	V445 Cep	Comparison	Check
Identifier	BD + 71°1109	BD + 71°1108	HD 210369
RA (2000)	$22^{h}07^{m}10.^{s}89$	$+2^{h}07^{m}12.^{s}81$	$22^{h}06^{m}43.^{s}28$
Dec (2000)	+ 72°22'22."2	+ 72°11'47."7	+ 72°13'41."6
V	$6.^{m}84$	$9.^{m}26$	$7.^{m}38$
Sp	A2V	F8	K2

Table 2. Observed times of minimum of V455 Cep.

HJD (2450000.0+)	Min. Type	HJD (2450000.0+)	Min. Type
5081.1091 ± 0.0021	I	5103.1017 ± 0.0065	I

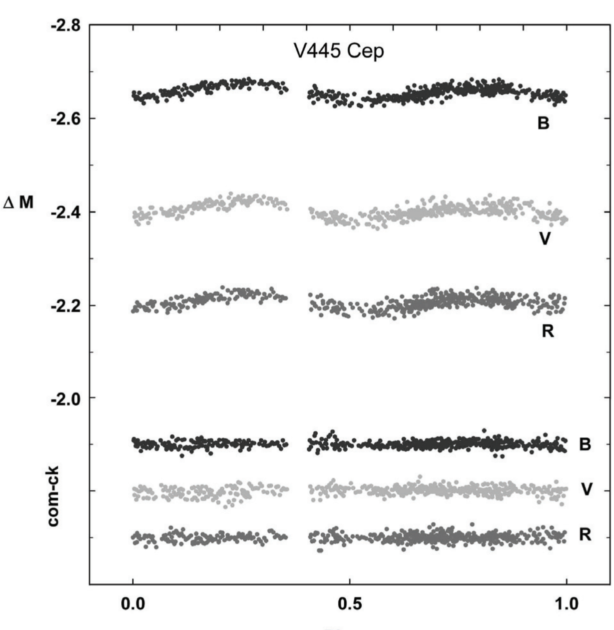

Fig. 1. Observed 3 color (B,V, R) CCD light curves of V445 Cep.

3. THE ORBITAL ELEMENTS OF V445 CEP AND THE SOLUTION

As mentioned in the introduction, the complete light curve of V445 Cep as well as the orbital elements, the solution, and the absolute dimensions have not been published. Thus, we have analyzed the new *BVR* CCD light curve and the radial velocity curve published by Pych et al. (2004) for the photometric and spectroscopic solutions. First we normalized magnitude difference to unit by adding $2.^{m}686$, $-2.^{m}442$, and $-2.^{m}240$ to *BVR* light curves, respectively and converted magnitude scale to intensity scale for using 2005 version of Wilson et al. (1971) differential correction method. We used mode 3 of the Wilson and Devinney code because V445 Cep has been already known as a contact binary of W UMa type (Duerbeck 1997, Eker et al. 2009, Pych et al. 2004, Rucinski 2002). As reported by the spectroscopic observations of Grenier

Table 3. Orbital elements and solutions of V445 Cep.

Element	B	V	R
a ($R_{\odot}$)		3.898 ± 0.210	
Vo (km/sec)		40.69	
i (degree)		19.58 ± 1.09	
q		0.167	
T_1 (K)		9,015	
T_2 (K)		8,460 ± 315	
$\Omega_1 = \Omega_2$		2.0930 ± 0.0166	
$L_1 / (L_1 + L_2)$	0.8568 ± 0.0645	0.8517 ± 0.0585	0.8488 ± 0532
r_1 (pole)		0.5142 ± 0.0045	
r_1 (side)		0.5941 ± 0.0070	
r_1 (back)		0.4907 ± 0.0087	
r_2 (pole)		0.2373 ± 0.0052	
r_2 (side)		0.2492 ± 0.0063	
r_2 (back)		0.3017 ± 0.0161	
$x_1 = x_2$	0.544	0.456	0.361
x_1 (bol), x_2 (bol)		0.654 0.655	
y_1(bol), y_2(bol)		0.099 0.099	

$f[=(\Omega_{in} - \Omega)/(\Omega_{in} - \Omega_{out})] = 0.516$
The subscripts 1 and 2 refer to the primary and secondary stars, respectively.

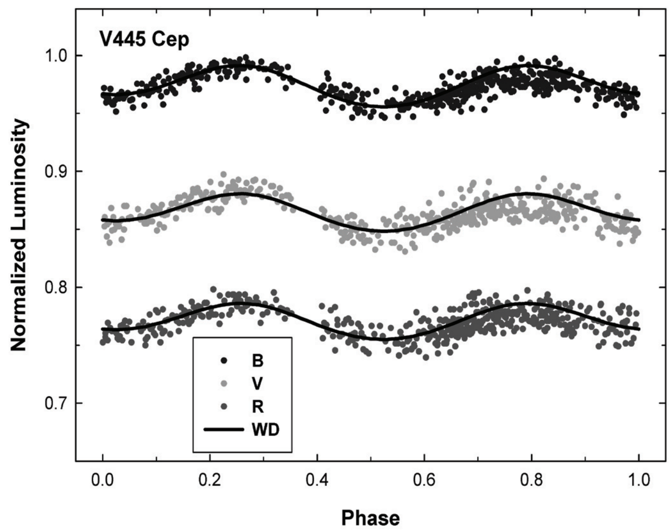

Fig. 2. Observed light curves (dots) and theoretical light curves (solid line) based on the WD model of V445 Cep.

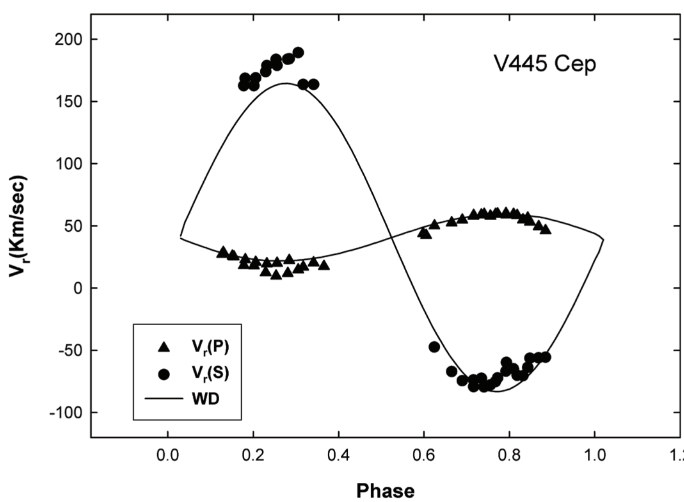

Fig. 3. Radial velocity curves (dots) of Pych et al. (2004) and theoretical light curves (solid line) based on the WD model of V445 Cep.

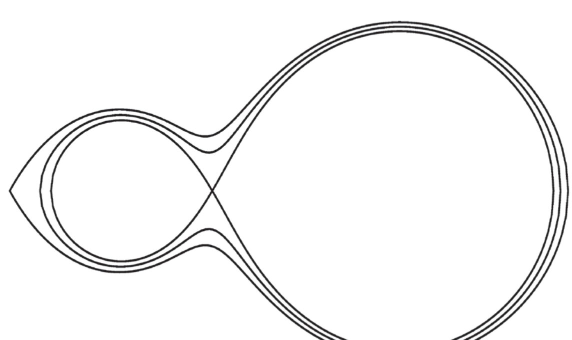

Fig. 4. Roche configuration of V445 Cep.

et al. (1999) and Pych et al. (2004), The temperature of the primary star was fixed to 9,015 K because its spectral type was determined as A2V by de Jager et al. (1987). The gravity darkening exponents ($g_1 = g_2$) and the bolometric albedos ($A_1 = A_2$) were all fixed to 1.0. The limb darkening coefficients ($x_1 = x_2$) and the coefficients of the bolometric limb darkening low, x_1 (bolo) and x_2 (bolo) were taken from Van Hamme (1993) and fixed as the initial values. Moreover, the system velocity Vo, and the mass ratio, q, were fixed as the values from Pych et al. (2004). Although the light curve of V445 Cep shows a little asymmetric, the asymmetry of the curve was not taken into account for the analysis because of large observational scatters. Figs. 2 and 3 shows normalized *BVR* light curves observed in this paper and radial velocity curves (Pych et al. 2004) of V445 Cep fitted by WD model. Filled Circles and solid lines are observations and computed light curves using mode 3 for contact binary systems, respectively. Table 3 lists the photometric and spectroscopic parameters, including relatively size of each star, of V445 Cep obtained by using the Wilson and Devinney program. Fig. 4 shows the Roche configuration of V445 Cep.

The spectral types of the contact binaries with low mass ratio belong to F or G types. However the spectral type of V445 Cep is A2V, which is an early type. Thus, we tried to use mode 2 (for detached system) for the light curve analysis where most parameters were also conversed. The parameters conversed in Mode 2 are not physically reasonable. Therefore we concentrate on mode 3 (for contact system) in this analysis.

4. RESULT AND DISCUSSION

We presented the complete *BVR* light curves of V445 Cep using CCD photometric observation. These are multicolor light curves for the first time. We have analyzed the multicolor light curves with the radial velocity curves

Table 4. Physical parameters of V455 Cep and low mass ratio contact binary stars.

Star	type	Sp.	P	q	$M_1/M_\odot$	$M_2/M_\odot$	$R_1/R_\odot$	$R_2/R_\odot$	$L_1/L_\odot$	$L_2/L_\odot$	log T_1	log T_2	Ref.
AW UMa	A	F0	0.4387	0.07	1.52	0.11	1.60	0.53	6.06	0.56	3.856	3.837	Maceroni et al. (1996)
SX Crv	A	F6/7V	0.3166	0.078	1.246	0.098	1.347	0.409	2.59	0.21	3.802	3.789	Zola et al. (2004)
V870 Ara	W	F8	0.3997	0.082	1.503	0.123	1.67	0.61	2.96	0.50	3.767	3.793	Szalai et al. (2007)
FP Boo	A	F0V	0.6404	0.101	1.77	0.17	2.31	0.85	13.46	1.38	3.855	3.840	Oh et al. (2009)
∈CrA	A	F0	0.5914	0.11	1.76	0.20	2.20	0.79	11.07	1.08	3.851	3.822	Maceroni et al. (1996)
GR Vir	A	F7/8V	0.3468	0.122	1.37	0.17	1.41	0.59	2.68	0.41	3.796	3.781	Oh et al. (2004)
TZ Boo	A	G9	0.2971	0.13	0.79	0.10	1.05	0.32	0.57	0.07	3.69	3.722	Rovithis-Livaniou et al. (1992)
UY UMa	W	G0	0.376	0.13	1.19	0.16	1.40	0.63	1.58	0.42	3.74	3.771	Yang et al. (2001)
V677 Cen	A/W	G2	0.3251	0.14	1.06	0.15	1.19	0.51	1.39	0.27	3.759	3.766	Maceroni et al. (1996)
FG Hya	A	G0	0.3278	0.14	1.08	0.15	1.27	0.53	1.75	0.29	3.771	3.764	Lu et al. (1999), Yang et al. (2000)
HN UMa	A	F8V	0.3826	0.14	1.91	0.19	1.42	0.61	2.72	0.41	3.796	3.774	Lee et al. (2006)
V776 Cas	A	F2V	0.4404	0.145	1.71	0.25	1.77	0.81	6.83	1.39	3.848	3.845	Oh et al. (2005)
HV Aqr	A	F5V	0.3744	0.145	1.43	0.22	1.45	0.66	3.63	0.80	3.822	3.830	Oh et al. (2004)
TV Mus	A	G0,F2	0.4457	0.15	1.32	0.20	1.66	0.75	3.14	0.69	3.777	3.784	Maceroni et al. (1996)
EF Dra	A	F9	0.424	0.16	1.81	0.29	1.70	0.77	3.31	0.71	3.778	3.782	Pribulla et al. (2001)
V410 Aur	A	G0/2V	0.3663	0.16	1.14	0.18	1.33	0.62	1.95	0.42	3.774	3.775	Oh et al. (2005)
V445 Cep	A	A2V	0.4487	0.167	3.39	0.57	2.18	1.02	27.73	4.71	3.955	3.927	This paper
AH Aur	A	F7V	0.4942	0.169	1.683	0.284	1.853	0.891	3.33	1.01	3.793	3.788	Pribulla et al. (2002)
II UMa	A	F5III	0.8252	0.172	2.14	0.37	2.91	1.42	12.72	2.87	3.807	3.802	Lee et al. (2006)
OU Ser	A/W?	F9/G0V	0.2967	0.173	1.018	0.176	1.088	0.505	1.33	0.38	3.775	3.805	Vanko et al. (2001)
RR Cen	A	F5,F2	0.6057	0.18	1.80	0.32	2.15	0.96	11.44	2.19	3.860	3.856	Maceroni et al. (1996)
XY Boo	A	F8	0.3705	0.18	1.49	0.27	1.47	0.63	5.17	1.01	3.857	3.851	Maceroni et al. (1996)
MW Pav	A	A5	0.795	0.18	2.13	0.39	2.7	1.31	22.1	5.05	3.882	3.879	Maceroni et al. (1996)
TY Pup	A	A9	0.8192	0.18	2.30	0.42	2.84	1.39	26.91	5.75	3.892	3.879	Gu et al. (1993)
Y Sex	A	F8	0.4198	0.20	0.76	0.15	1.20	0.54	2.23	0.40	3.810	3.800	Hilditch et al. (1988)

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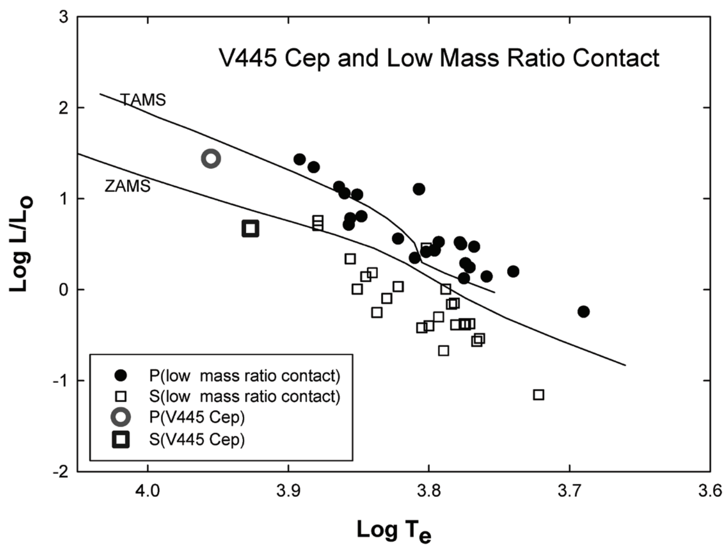

Fig. 5. H-R diagram of V445 Cep and low mass contact binary stars. P and S stand for primary and secondary stars, respectively.

of Pych et al. (2004) by the method of the Wilson and Devinney Differential correction. Table 3 lists photometric and spectroscopic parameters of V445 Cep. The light variation was also confirmed by the multicolor *BVR* light curve. The amplitude of curves are 0.028 mag in B, 0.026 mag in V, and 0.025 mag in R, respectively. Such small variation is very rare.

We have discovered O'Connell effect that shows two different maxima and the secondary eclipse is deeper than primary eclipse indicating the possibility that the primary eclipse and the secondary eclipse might have been switched. A continued photometric observation is necessary to investigate the possibility of such change.

We list the absolute dimensions of 24 low mass ratio contact binary systems and V445 Cep in Table 4, in order to compare the absolute dimension of V445 Cep to those of the 24 low mass ratio contract binaries (Oh et al. 2009). Except for V870 Ara and UY UMa, the 22 contract binaries belong to A-type of contract binary. The spectral types of their primary stars are F or G. Their orbital periods are less than 0.8 day, mostly being less than 0.5 day. The masses of the binary systems are mostly in the range of $1M_{\odot}$ to $2M_{\odot}$.

V445 Cep is a A-type contact binary. The mass ratio and period of V445 Cep are similar to those of 24 low mass ratio contact binaries while spectral type and mass, and size are different from those of 24 low mass ratio contact binaries. The spectral type and mass of the primary and secondary stars of V445 Cep is A2V and $3.96M_{\odot}$ and $0.57M_{\odot}$ which are a earliest type and highest mass in the low mass ratio contact binaries.

As shown in Fig. 5, the primary stars of the low mass ratio contact binaries are located in the more evolved location than the terminal age main sequence (TAMS), while their secondary stars are located at the location in lower luminosity than the zero-age main sequence (ZAMS). The primary star and the secondary star of V445 Cep are located in higher temperature and high luminosity region when compared with the 24 low mass ratio contact binaries.

If V445 Cep is classified as a group of low mass ratio contact binary, then the characteristics, including spectral type, mass and luminosity of the group will be extended.

Our light curves show the secondary eclipse is deeper than the primary eclipse. We need to investigate whether the deeper secondary minimum is due to observational scatter or wrong light element for future work.

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