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PHOTOMETRIC STUDY OF THE NEAR-CONTACT BINARY CN ANDROMEDAE

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ABSTRACT

We completed four color light curves of the near-contact binary CN And during three nights from September to December 2004 using the 61-cm reflector and *BVRI* filters at Sobaeksan Observatory. We determined four new times of minimum light (two timings for primary eclipse, two for secondary). Newly obtained *BVRI* light curves and the radial velocity curves from Rucinski et al. (2000) were simultaneously analyzed to derive the system parameters of CN And. We used the semi-detached mode 4 of the 2003-version of the Wilson-Devinney binary model, and interpreted the asymmetry of the light curve by introducing two spots; a cool spot on the primary component and a hot spot on the secondary component. New photometric parameters are not much different from those of Çiçek et al. (2005), and it is considered that the system is in the era of broken contact. From the orbital period study with all available timings including our data, we found a continous period decrease with a rate of $\dot{P}_{obs} = - -1.82 \times 10^{-7}$ d yr^{-1} that can be explained with two possible mechanisms. We think the most likely cause of the period decrease is a thermal mass transfer from the primary to the secondary component, rather than angular momentum loss due to a magnetic stellar wind.

Key words : binaries: close — star: individual (CN Andromedae) — stars: mass transfer

I. INTRODUCTION

Shaw (1994) defined near-contact binaries (NCBs) as having orbital periods less than one day and showing strong tidal interaction. Although they have that closest surfaces are separated by less than 10 percent of their orbital radius, they are not in contact. Most of them have the spectral type of A or F for primary and G or K for secondary, and NCBs are considered to be an evolutionary precursor of the A-subtype W UMa binaries.

Lucy (1976), Flannery (1976), and Robertson & Eggleton (1977) suggested TRO (thermal relaxation oscillation) mechanism. It is a non-equilibrium model, in which systems undergo cyclic thermal relaxation oscillations about a state of marginal contact. The binaries alternate between era of good thermal contact, during which they show EW-type light curves and era of broken contact, during which they show EB-type light curves. Robertson & Eggleton (1977) also predicted that the broken contact stage is shorter than the contact stage, so only a small portion of the observed EW-type systems were expected to show EB-type light curves. To examine the theory, Van Hamme et al. (2001) have catalogued 34 TRO candidates, which show EW-type light curves.

The light variation of CN And (RA=00^h 20^m $30^s.6$, DEC=$+40°$ $13'$ $33''.8$) was first announced by Hoffmeister (1949). Löchel (1960) found the light curve to be of EW-type with 0.462798 days. Bozkurt et al. (1976) emphasized the asymmetries in *B* and *V* light curves. Kaluzny (1983) argued the system to be a EB-type rather than EW-type using their *BV* light curve analysis. Yang and Liu (1985) reported two flare events in 1981. The study of light curve asymmetries of the system was provided by Rafert et al. (1985), Keskin (1989), Branly (1992), Samec et al. (1998). Shaw et al. (1996) derived $\log L_X = 30.55$ erg s^{-1} from ROSAT All-Sky Survey (RASS) data, and it is similar to the value of RS CVn stars, which is $< \log L_X > = 30.35$ erg s^{-1} (Dempsey et al. 1993).

Rucinski et al. (2000) derived orbital parameters and suggested CN And as an EW A-subtype contact binary from their spectroscopic study. Van Hamme et al. (2001) collected four light curves, which were obtained from 1983 to 1997. They reanalyzed them and concluded that the photometric and spot parameters were not changed largely. Çiçek et al. (2005) analyzed their own *BVR* light curves which obtained in 2001, and concluded their solutions are similar to those of Van Hamme et al. (2001).

On the other hand, the orbital period changes of CN And were presented several times. Although Seeds & Abernethy (1982) did not find any evidence for a

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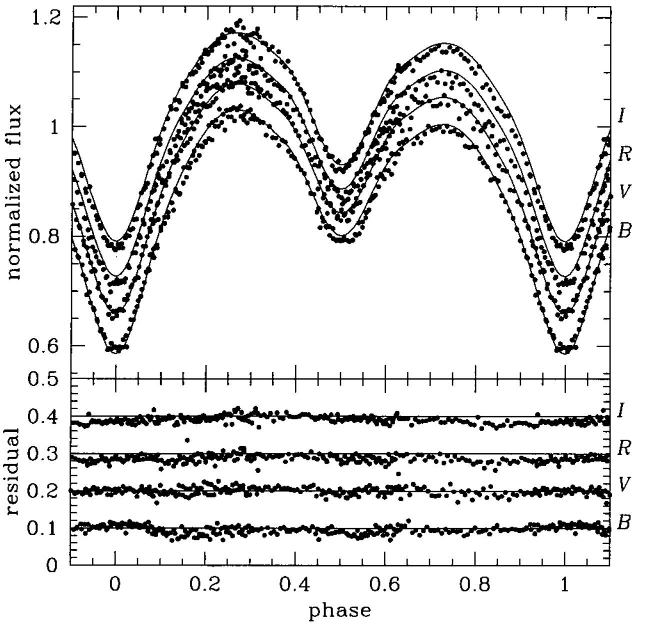

Fig. 1.— Light curves of CN And. Solid lines represent the theoretical curves with our solution.

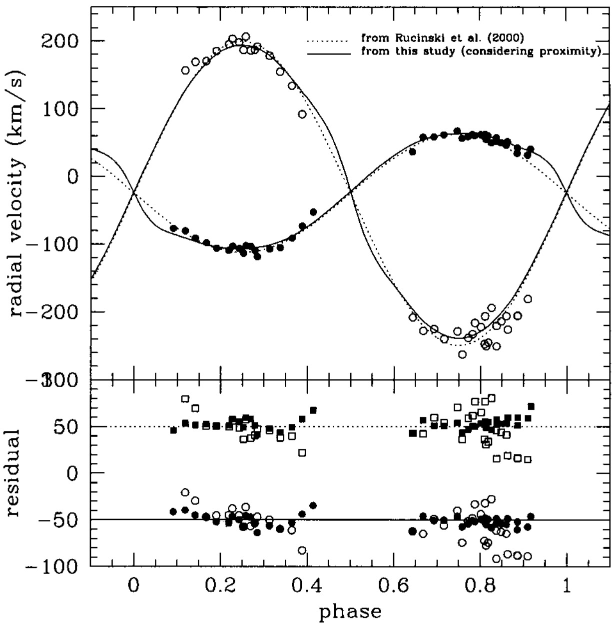

Fig. 2.— Radial velocity curves of CN And. Solid lines represent the theoretical curves in including proximity effects. Dotted lines represent the theoritical curves from Rucinski et al. (2000).

change in period, Kaluzny (1983) introduced quadratic term in the *O–C* residuals. Evren et al. (1987) found the orbital period to be decreasing with the rate of $\dot{P} = -7.41 \times 10^{-8}$ d yr^{-1}, which was modified by Samec et al. (1998) to be $\dot{P} = -1.55 \times 10^{-7}$ d yr^{-1}. Van Hamme et al. (2001) put the decreasing rate of -0.0195 s yr^{-1} (= -2.26×10^{-7} d yr^{-1}) and derived a conservative mass transfer rate of $\dot{M} = 1.4 \times 10^{-7}$ M$_\odot$ yr^{-1}. Çiçek et al. (2005) concluded that the orbital period has a secular decrease of about -1.98 ± 0.04 s per century (= -2.29×10^{-7} d yr^{-1}), which corresponds to a conservative mass transfer from primary to secondary component at a rate of $1.52 \pm 0.09 \times 10^{-7}$ M$_\odot$ yr^{-1} or a mass loss from the primary due to magnetic stellar winds at a rate of $7.83 \pm 0.09 \times 10^{-8}$ M$_\odot$ yr^{-1}. In this paper, the results of new CCD photometry for CN And are presented together with a light curve synthesis and a period analysis.

II. OBSERVATION AND DATA REDUCTION

We observed CN And using the 61-cm telescope at Sobaeksan Observatory for 3 nights in 2004. Because the telescope has an enclosed tube assembly structure, stray light effects from near bright stars and nearby village lights are smaller than those of Mt Lemmon Observatory and Bohyunsan Observatory. The LN2 cooled CCD camera, which covers 20′.5×20′.5, and Johnson *BVRI* filters were used and sky flat and bias images were obtained during early evening and early morning. The Dipho (Kim et al. 2001) program was used while observing CN And. It displays the light curve on the screen promptly and corrects the positional error after taking an image by itself. To reduce the CCD readout time, the CCD was set to 2 × 2 binning mode. Considering the linear range of the CCD, the exposure times of *BVRI* bands were set to 25, 15, 10, and 10 seconds, respectively. The FWHM of the star image was kept to 2.0 during observation.

All images were preprocessed with the CCDRED package and then processed with the APPHOT photometry package in IRAF software. All processes for the data reduction were performed using the data reduction scripts (Lee et al. 2003). In the script, the averaged FWHM of stars is estimated by measuring those of ten-bright stars, which were not saturated in the image, and 4 times of the value was used as the radius of aperture.

The GSC2787-1843 (RA=00^h 20^m 36^s.3, DEC=+40° 18′ 38″.7) and the GSC2786-0494 (RA=00^h 19^m 55^s.4 DEC=+40° 09′ 59″.0) were chosen as comparison and check stars, respectively. Because the colors of two stars are very similar to that of CN And, any correction for color extinction effect was not made.

We obtained a total of 819 indivisual observations (*B*: 206, *V*: 206, *R*: 202, *I*: 205; all reduced data can be available through *http://kasi.re.kr/~leecu/cn_and.mag.txt*) with the standard deviation of about ± 0.011 mag in each band. The standard deviation was esti-

Table 1.
New times of minima for CN And

HJD	Error	Filter	Type
2453273.2145	±0.0003	B, V, R, I	II
2453338.9296	±0.0006	B, V, R, I	II
2453339.1590	±0.0002	B, V, R, I	I
2453341.0093	±0.0003	B, V, R, I	I

mated from the magnitude difference between the check and comparison stars. From our observations, times of minimum light in each color have been determined using the method of Kwee & van Woerden (1956). Four new times of minimum light, which are weighted means from the observations in the separate bandpasses, are given in Table 1.

III. LIGHT CURVE ANALYSIS

To analyze the newly obtained *BVRI* light curves and the radial velocity curves from Rucinski et al. (2000) simultaneously. we used mode 4 of the 2003 W-D binary code (Wilson & Devinney 1971). In the analysis, we adopted reasonable parameter values from various literatures as follows: the temperature of primary component T_1 was assumed to be 6500K corresponding to the spectral type of F5V (Rucinski et al. 2000, de Jager & Nieuwenhuijzen 1987); the logarithmic limb-darkening coefficients of bolometric X_1, Y_1, X_2, Y_2 and x_1, y_1, x_2, y_2 for monochromatic bands were taken from Van Hamme (1993); the gravity-darkening exponents g_1, g_2 were set to 0.32 for convective envelopes (Lucy 1967); the bolometric albedos A_1, A_2 were fixed to 0.5 for convective envelopes (Rucinski 1969); synchrotron rotation $F_1 = F_2 = 1$ and circular orbit $e = 0$ were assumed. The data were weighted as inversely proportional to the square root of the light level. The double reflection was used as detailed reflection treatment. These parameters are kept constant during iteration.

The first time derivative of the orbital period $\dot{P}$ is fixed as -4.98×10^{-10} ($= -1.82 \times 10^{-7}$ d yr^{-1}) which is obtained from *O–C* analysis. To find better solution, some parameters were set to be adjustable; the ephemeris parameters T_0, P, the semi-major axis a, the system velocity V_γ, the orbital inclination i, the temperature T_2 and the dimensionless surface potentials Ω_2 of secondary, mass ratio q=m_2/m_1, and the monochromatic luminosity of the primary component L_1. In this paper, the subscripts 1 and 2 represent the primary (hotter) and secondary (cooler) components, respectively.

The strong asymmetry between the maxima (Max I and Max II) of the light curve and the assumption of convective envelope from F5V spectral type suggest that the system could have spots. The large scattered residual in the lower panel of Figure 1 indicates spot activities. Two spots were assumed; a cool spot on the primary and a hot spot on the secondary component. Due to the semi-detached configuration of the system, mass from the primary can flow to the secondary. It is also possible to make a hot spot near the neck of the Roche configuration.

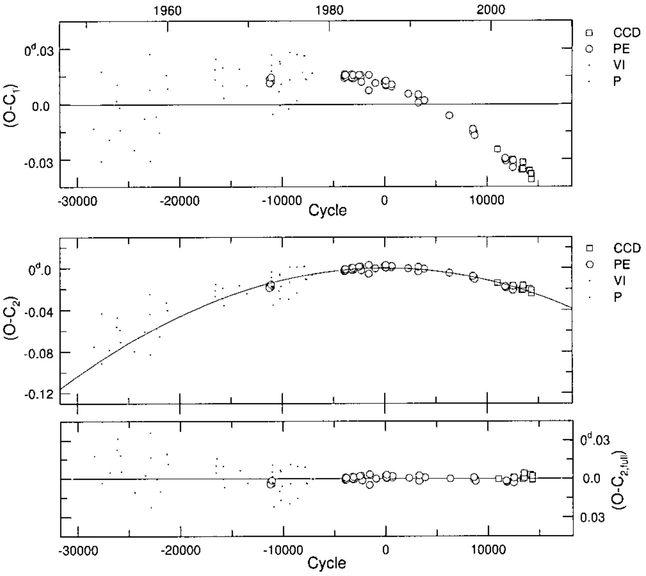

Fig. 3.— The upper and middle panels show the *O–C* diagrams of CN And constructed with the linear terms of Kreiner et al. (2001) and our least-squares quadratic fit, respectively. Timings are marked by assorted symbols differing in size and shape according to different observational methods. In the middle panel, the continuous curve represents the quadratic term of equation (2). The residuals from the full ephemeris are plotted in the lower panel.

To get the convergent solutions of the system, we made an iterating script program that finds the best parameters by iteration and gives a graphical result. Table 2 represents the newly obtained parameters from this study. As a result of the iteration, two graphical results were obtained; Figure 1 represents the observed and computed light curves, and Figure 2 represents the newly fitted radial velocity curves with photometric solution.

IV. ORBITAL PERIOD STUDY

A total of 117 archival timings (34 sky patrol, 16 visual, 55 photoelectric and 12 CCD), including our own measurements, have been collected to study the period variability of CN And. The *O–C* residuals for the timings were calculated using the light elements of Kreiner et al. (2001):

TABLE 2.
PHOTOMETRIC SOLUTION OF CN AND

Parameter	Branly et al. (1992)		Çiçek et al. (2005)		this study	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
T_0(HJD)	2446714.70769(35)		2452185.4226(1)		2446711.53184(8)	
P(d)	0.4627997(29)		0.46278845(3)		0.46279252(1)	
$\dot{P}$	$-6.18 \times 10^{-10}(17)$		$-6.27 \times 10^{-10}(13)$		$-4.98 \times 10^{-10}(4)$	
i(°)	68.72(68)		68.02(15)		69.9(1)	
V_γ(kms^{-1})	—		-25.89(66)		-22.3(9)	
a($R_\odot$)	—		3.16(2)		3.00(1)	
q	0.38845		0.3935(20)		0.3902(5)	
f(%)^c	100		99		99	
T(K)	6500^a	5860(210)	6500^a	5947(12)	6500^a	5890(4)
Ω	2.654(15)	2.654(18)	2.6673(59)	2.6673(59)	2.6576(22)	2.6450(22)
X	0.639^a	0.645^a	0.638^a	0.644^a	0.638^a	0.644^a
Y	0.240^a	0.214^a	0.241^a	0.209^a	0.241^a	0.209^a
x_B	0.805^a	0.833^a	0.805^a	0.837^a	0.805^a	0.837^a
y_B	0.236^a	0.157^a	0.232^a	0.138^a	0.232^a	0.138^a
x_V	0.710^a	0.753^a	0.710^a	0.760^a	0.710^a	0.760^a
y_V	0.277^a	0.243^a	0.275^a	0.233^a	0.275^a	0.233^a
x_R	0.617^a	0.661^a	0.616^a	0.668^a	0.616^a	0.668^a
y_R	0.283^a	0.259^a	0.284^a	0.254^a	0.284^a	0.254^a
x_I	—	—	—	—	0.553^a	0.605^a
y_I	—	—	—	—	0.277^a	0.252^a
$L/(L_1+L_2)_B$	0.817(27)	0.183	0.7982(20)	0.2018	0.8140(29)	0.1860
$L/(L_1+L_2)_V$	0.792(26)	0.208	0.7778(26)	0.2222	0.7890(25)	0.2110
$L/(L_1+L_2)_R$	0.777(24)	0.223	0.7649(22)	0.2351	0.7737(23)	0.2263
$L/(L_1+L_2)_I$	—	—	—	—	0.7618(21)	0.2382
r(volume)^b	0.4648(40)	0.3003(51)	0.4692(15)	0.2986(21)	0.4644(15)	0.3040(15)
Spot parameter:						
colatitude(°)	25(31)	75.3(70)	22.6(45)	83.1(2)	19.8(2)	87.5(20)
longitude(°)	8.5(8.7)	1.3(49)	17.5(35)	1.3(3)	11.5(2)	3.6(23)
radius(°)	29(16)	20.1(52)	32.1(64)	20.1(4)	34.9(1)	23.3(21)
$T_{\rm spot}/T_{\rm star}$	0.65^a	1.150(64)	0.65^a	1.093(22)	0.65^a	1.092(14)

^{a}: fixed parameter, ^{b}: mean volume radius, ^{c}: Roche lobe filling = Ω_{in} / Ω

$$C_1 = \mathrm{HJD}2446711.522 + 0.^{\rm d}46279428\mathrm{E}, \qquad (1)$$

The resultant O–C_1 diagram constructed with equation (1) is shown in the upper panel of Figure 3, where the times of minimum light are marked by assorted symbols differing in size and shape according to the observational methods. Despite the very large scatter of about $0.^{\rm d}03$ for the sky-patrol and visual residuals, it seems that the orbital period of CN And has been continuously decreasing as suggested by Van Hamme et al. (2001) and Çiçek et al. (2005). Therefore, we introduced all times of minimum light into a least-squares quadratic fit to obtain the following ephemeris:

$$\begin{aligned} C_2 = \ & \mathrm{HJD}2446711.53184(8) + 0.^{\rm d}462792448(8)\mathrm{E} \\ & -1.^{\rm d}153(8) \times 10^{-10}\mathrm{E}^2, \qquad (2) \end{aligned}$$

The parenthesized numbers are the 1σ-error values for the last digit of each term of the ephemeris. In this analysis, we assigned weights of 7 to photoelectric and CCD minima and 1 to all others. Our quadratic term is slightly smaller than those of the previous researchers. The O–C_2 residuals with respect to the linear term of the equation (2) are plotted in the middle panel of Figure 3, where the continuous curve represents the quadratic term of the equation (2) and the residuals from the full ephemeris are plotted in the lower panel. As can be seen, the quadratic ephemeris provides a good fit to the mean trend of the O–C residuals. The coefficient of the quadratic term is negative and indicates a continuous period decrease with a rate of $\dot{P}_{\rm obs} = -1.82 \times 10^{-7}$ d yr^{-1}. In principle, such a period variation can be interpreted as mass transfer from the more massive to the less massive component or as angular momentum loss (hereafter AML).

If the secular period decrease is produced by AML due to magnetic braking, we can calculate the decreasing rate of period change with the following formula (Guinan & Bradstreet 1988):

$$\dot{P}_{\rm mb} \approx \quad -1.1 \times 10^{-8} q^{-1} (1+q)^2 (M_1+M_2)^{-5/3} k^2$$

$$\times(M_1R_1^4 + M_2R_2^4)P^{-7/3}, \qquad (3)$$

where $M_{1,2}$ and $R_{1,2}$ are the masses and radii of the components in solar units, respectively. Also, q is the mass ratio (M_2/M_1) and k^2 is the gyration constant associated with the stellar moment of inertia $I{=}k^2MR^2$. With $k^2{=}0.1$ (see Webbink 1976) and with the absolute dimensions determined by Çiçek et al. (2005), a period decrease rate of $\dot{P}_{mb} = -7.6\times10^{-8}$ d yr^{-1} is obtained, which is too small compared with the observed value by a factor of about 60%. Therefore, with AML alone it can be difficult to explain fully the observed secular period decrease of CN And.

The other possible mechanism is a conservative mass transfer from the more massive primary to the less massive secondary star, as follows (Pringle 1975):

$$\frac{\Delta P}{P} = \frac{3(M_1 - M_2)}{M_1M_2}\Delta M_1, \qquad (4)$$

Using again the masses of Çiçek et al. (2005), we get the mass transfer rate as $\dot{M}_1 = -1.21 \times 10^{-7}$ $M_\odot$ yr^{-1}. Let us assume that both the orbital angular momentum and the total mass of the system remain constant and that the primary star transfers its present mass to the secondary component on the thermal time scale defined as $\tau_{th}{=}(GM_d^2)/(R_dL_d)$ (Paczyński 1971). Then, $\tau_{th}{=}1.21\times10^7$yr and mass is transferred to the companion (secondary) at a rate given roughly by $M_d/\tau_{th}{=}1.18\times10^{-7}M_\odot$ yr^{-1}, which is consistent with the mass transfer rate inferred from our quadratic term. Here, M_d, R_d and L_d denote the present mass, radius and luminosity of the donor (primary) star, respectively. Therefore, we think that the continuous period decrease of CN And may be caused by a thermal mass transfer from the primary to the secondary component. rather than AML due to a magnetic stellar wind.

V. SUMMARY AND DISCUSSION

We present the simultaneous solution using newly obtained *BVRI* light curve and the radial velocity curve of Rucinski et al. (2000). The newly derived parameters show that there is no big change in CN And system. We obtained two times of minimum light at each eclipse, and derived a continuous period decrease with a rate of $\dot{P}_{obs} = -1.82\times10^{-7}$ d yr^{-1}.

Two possible mechanisms with new result were examined and concluded that the continuous period decrease of CN And may be caused by a thermal mass transfer from the primary to the secondary component, rather than angular momentum loss due to a magnetic stellar wind. Although there is no significant system variation, it is expected to observe continuously to examine the TRO theory.

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