CCD Photometry of the Eclipsing Binary V376 Andromedae

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Abstract

We present CCD BVR_CI_C light curves of W UMa type eclipsing binary V376 And. The obtained light curves are confirmed to show the O'Connell effect, as has been found in HIPPARCOS light curve, and the effect is found less significant in redder light. We made a preliminary analysis of the V light curve to obtain photometric elements of the binary system, assuming that there is a dark spot on the trailing side of the primary component's surface. By combining these elements with published orbital elements, we obtained the absolute dimensions of both components. We secured six times of minima in our observations, and made a brief period study based on all the available observed minima.

1. Introduction

V376 And (=HIP 012039, $P = 0.799$ d, $V = 7.70$–7.96) was found as a W UMa-type eclipsing binary by the HIPPARCOS mission (ESA 1997). The spectral type of the binary is given as A4 (Rucinski et al. 2001), which is an unusually early spectral type for W UMa type binaries. In fact, the existence of a W UMa type with such an early spectral type should be very important from the point of view that a good thermal contact between both components, as pointed by Rucinski et al. (2001).

Although many photoelectric and CCD minima of V376 And have been reported (Keskin et al. 2000, Tanriverdi et al. 2003, Dumitrescu et al. 2004, Porowski 2005, Dróżdż and Ogłoza 2005, Albayrak et al. 2005, Hübscher et al. 2006, Csizmadia et al. 2006, Nelson 2007), neither photoelectric nor CCD light curves have been published so far except for the photoelectric BV light curves by Dumitrescu et al. (2005). On the other hand, Rucinski et al. (2001) obtained a radial velocity curve of a good quality for this binary. As far as we know, however, no physical property of the system has been deduced so far.

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In this study, we examine the physical property of this unusual W UMa type binary V376 And on the basis of our CCD photometric observations and the orbital elements given by Rucinski et al. (2007). In the next section, we describe our photometric observations and the results. In section 3, we make a period study of the eclipsing binary using the present and the published data. In section 4, we make a preliminary analysis of the observed light curves, from which we deduce the absolute dimensions of both the components in section 5. In the final section, we briefly discuss the physical nature of the system.

2. Observations and Results

2.1. Observations

We made CCD photometric observations of V376 And in Aramaki campus of Gunma University on six nights in October 2002. We used a 30 cm Meade Schimidt-cassegrain telescope and a cooled CCD camera SBIG ST-7 with filters approximating Johnson-Cousine's $BVR_{\rm C}I_{\rm C}$ standard system. Typical integration times were 10 sec for V, 20 sec for $R_{\rm C}$ and 120 sec for B and $I_{\rm C}$. The total number of each filter observations is approximately 450. Table 1 lists the positions and magnitudes of V376 And and two comparison stars employed in our observations. These three stars were taken in the same CCD frames. No appreciable variation has been found in the magnitude difference between the two comparison stars, which suggests the constancy of the comparison stars within observational errors.

2.2. Results

We processed all the CCD photometric data with MIRA Pro Ver.6 (Axiom Research) software package. Since the two comparison stars are rather fainter than the variable by 1.6 − 2.2 mag, we have made use of a combined magnitude of the two stars, which corresponds to the sum of the two comparison star's light, in order to compute differential magnitudes (variable − comparison). We have corrected the differential magnitudes for atmospheric extinction. These differential magnitudes have not been transformed into Johnson-Cousine's standard system.

Fig.1 displays the differential magnitude of V376 And plotted against an orbital phase, which

Table 1 Positions and magnitudes of V376 And and the two comparison stars.

Star	RA (2000)	DEC (2000)	V	$B-V$
V376 And (=HIP 012039)	02h35m11.6s	+49°51′37″	7.70–7.96	+0.23
BD+49°703 (=TYC 3303.607.1)	02h35m48.6s	+49°54′05″	9.76	+0.10
BD+49°704 (=TYC 3303.1963.1)	02h35m54.5s	+49°51′43″	9.95	+1.54

Data are taken from HIPPARCOS/TYCHO Catalogue (ESA, 1997).

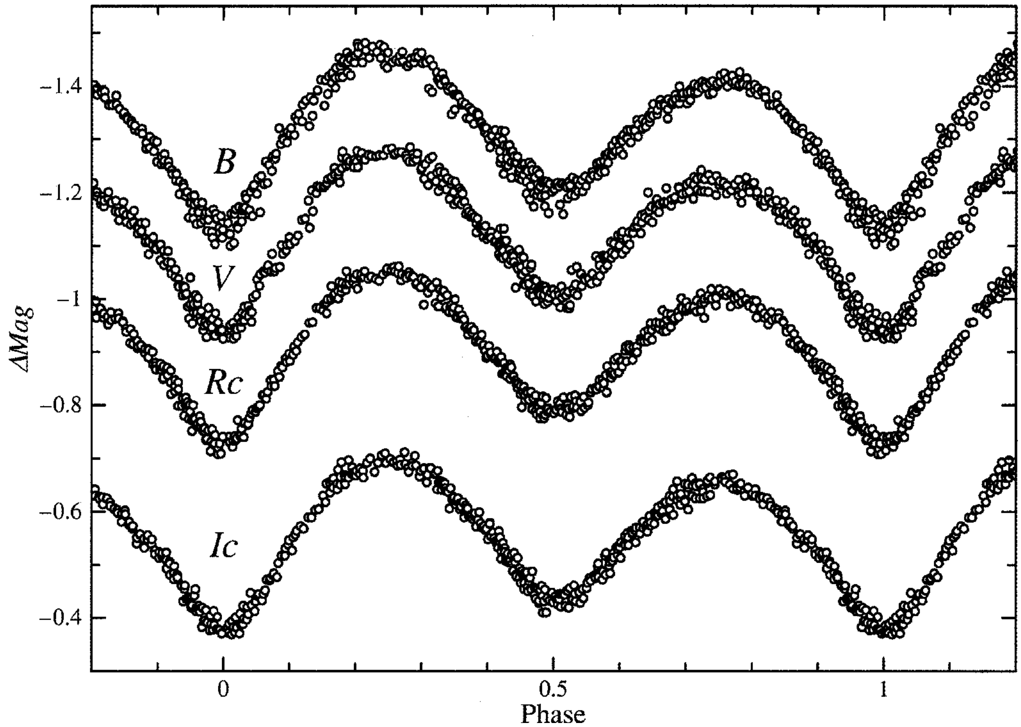

Fig. 1 The observed light curves of V376 And.

was computed with the ephemeris given by Dumitrescu et al. (2005). The light variation of V376 And is continuous, implying that both components are very distorted due to a proximity effect. The light curves also show so-called O'Connell effect. The first maximum (Max I) is brighter than the second maximum (Max II). The difference between both the maxima becomes less significant in redder light: ~ 0.06 mag in B and ~ 0.04 mag in I_C. All the data will be provided on request.[2]

In our observation of V376 And, we obtained six times of minima, three for the primary and another three for the secondary, using Kwee and van Woerden (1956) method. The results are given in Table 2 of the next section.

3. Period Study

Table 2 lists all the available observed minima of V376 Ori, including those obtained in our study, as mentioned in the preceding section.

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Table 2 Times of minima of V376 And collected in this study.

HJD 2400000+	E (cycles)	$(O-C)$ (days)	Method*	Source†
48500.7420	−5515.0	+0.0003		HIP‡
51510.5418	−1746.5	+0.0046	pe	IBVS 4855‡
51644.3215	−1579.0	+0.0068	sp	AJ 120‡
51865.53952	−1302.0	−0.00734	pe	ARB 20‡
52561.9839	−430.0	−0.0049	CCD	This study
52563.9859	−427.5	+0.0004	CCD	This study
52575.1706	−413.5	+0.0037	CCD	This study
52575.9692	−412.5	+0.0036	CCD	This study
52577.1582	−411.0	−0.0054	CCD	This study
52577.9589	−410.0	−0.0034	CCD	This study
52595.5273	−388.0	−0.0058	pe	IBVS 5407‡
52697.3649	−260.5	+0.0012	pe	IBVS 5623
52905.42037	0.0	+0.00257	pe	ARB 20‡
52911.41258	7.5	+0.00474	pe	ARB 20‡
52957.33934	65.0	+0.00786	pe	ARB 20‡
52965.31396	75.0	−0.00424	pe	ARB 20‡
52991.28162	107.5	+0.00658	pe	ARB 20‡
53252.4473	434.5	+0.0065	pe	IBVS 5606
53304.3583	499.5	+0.0038	pe	IBVS 5623
53305.5504	501.0	−0.0021	pe	IBVS 5623
53306.3455	502.0	−0.0056	pe	IBVS 5623
53314.3346	512.0	−0.0033	pe	IBVS 5649
53315.5360	513.5	+0.0001	pe	IBVS 5649
53346.2795	552.0	−0.0052	pe	IBVS 5657
53655.3697	939.0	−0.0011	pe	IBVS 5731
53990.8105	1359.0	−0.0025		AAVSO HP
54018.3694	1393.5	+0.0022	CCD	IBVS 5736
54011.9868	1385.5	+0.0089	CCD	IBVS 5760

* pe: photoelectric, sp: spectroscopically-determined.

† HIP: ESA (1997), IBVS 4855: Keskin et al. (2000), AJ 120: Rucinski et al. (2001), IBVS 5407: Tanriverdi et al. (2003), ARB 20: Dumitrescu et al. (2005) [The same data to four decimal places are also listed in IBVS 5599.], IBVS 5606: Porowski (2005), IBVS 5623: Dróżdż and Ogłoza (2005), IBVS 5649: Albayrak et al. (2005), IBVS 5657: Hübscher et al. (2005), IBVS 5731: Hübscher et al. (2006), IBVS 5736: Csizmadia et al. (2006), IBVS 5760: Nelson (2007), AAVSO HP: AAVSO, Eclipsing Binary $O-C$ Files (updated 2006-12-20), http://www.aavso.org/observing/programs/eclipser/omc/nelson_omc.shtml.

‡ These sources' data have been used by Dumitrescu et al. (2005) to deduce their ephemeris or equation (1).

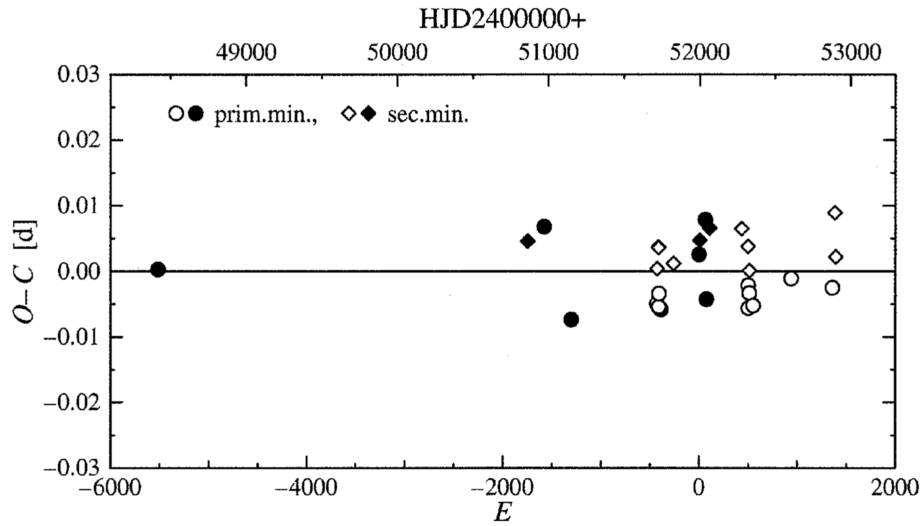

Fig. 2 $(O - C)$ diagram of V376 And constructed with the ephemeris of Dumitrescu et al. (2005). The filled symbols are the minima used by Dumitrescu et al. (2005) while open symbols are those newly collected in this study.

The ephemeris of V376 And has been deduced to be

$$\text{Min. I} = \text{HJD } 2452905.4178 + 0.798672\ E \tag{1}$$

by Dumitrescu et al. (2005). The third column of table 2 gives $(O - C)$ values based on this ephemeris. They are also displayed in Fig. 2. Most of the observed minima, including recent ones, are found to be within $\sim \pm 0.008$ d, which suggests that the above ephemeris can be satisfactorily applied for the epoch covering these minima.

$(O - C)$ values for the secondary minima seem systematically larger than those for the primary. In fact, the average and the standard deviation for the former are $+0.0039$ d and ± 0.0026 d, while those for the primary are -0.0021 d and ± 0.0043 d, respectively. The difference, whose significance is marginal, though, may be influenced by the light curve asymmetry where Max I is brighter than Max II as mentioned in the preceding section.

4. Light Curve Analysis

As shown in Fig.1, the light curves exhibit a significant asymmetry. In the present study, we confine our attention to the analysis of the V light curve to obtain preliminary photometric elements. Although we have no clear idea about the brightness distribution over both components' surface, we simply hypothesized that the primary (hotter) component has a dark spot on its trailing side surface.

Table 3 Preliminary photometric elements based on the V light curve.

System parameters		
Mass ratio	q	0.305 (fixed)
Orbital inclination	i	62.0°
Fill-out ratio*	f	1.98
Fractional radii (side)	r_1, r_2	0.548, 0.331
Fractional luminosities	l_1, l_2	0.866, 0.134
Limb darkening coefficients	u_1, u_2	0.49, 0.49 (fixed)
Gravity darkening exponents	α_1, α_2	1.0, 1.0 (fixed)
Bolometric albedo	A_1, A_2	1.0, 1.0 (fixed)
Dark spot parameters		
Longitude	λ_s	254°
Latitude	β_s	−15°
Radius	r_s	22°
Brightness factor	br_s	0.10
Residuals	$(O-C)^2$	0.06355

* The fill-out ratio (f) defined by Yamasaki (1981) is related to the so-called degree of overcontact ($f_{\rm over}$) by $f_{\rm over} = 2(1 - 1/f)$.

We will discuss this issue in the next section. We adopted Yamasaki's (1981) light-curve-synthesis with a spot model.

In general, the effective temperature of two component stars of W UMa type is considered not so different one from another. Then, we assume that the primary component has an effective

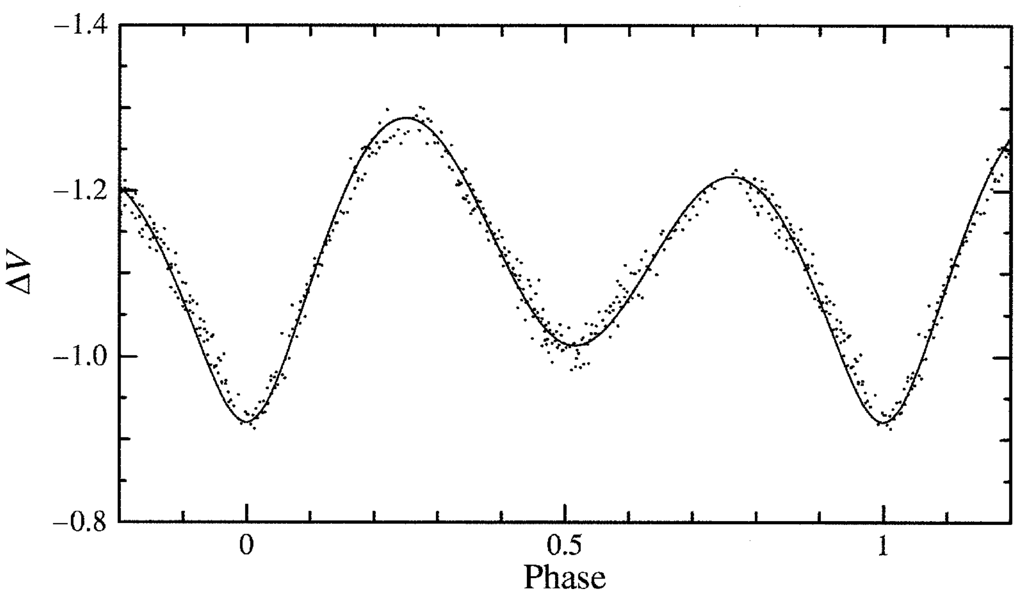

Fig. 3 Theoretical light curve fitted to V observations.

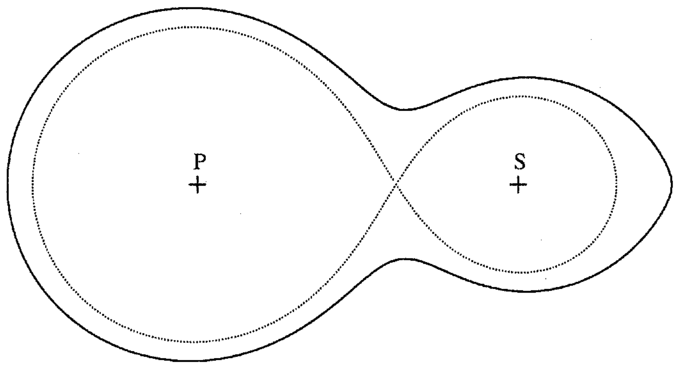

Fig. 4 Equatorial configuration of the components and the critical Roche lobe.

temperature $T_{\mathrm{eff},1} = 8400$ K (Cox 2000), corresponding to a spectral type of A4 (Rucinski et al. 2001) while the secondary has a temperature a little cooler than of the primary component. This suggests that the stellar atmospheres of both the components should be radiative. Therefore we took the gravity-darkening exponents (α) and the bolometric albedos (A) of both components as $\alpha = 1.0$ and $A = 1.0$, respectively. Employing a linear limb-darkening law and referring to the table of Van Hamme (1993), we adopted the linear coefficients (u_1, u_2) of both components as (0.49, 0.49) for V. We employed the mass ratio $q(= M_2/M_1) = 0.305$ given by Rucinski et al. (2001) from their radial velocity curve of V376 And.

As for the dark spot on the primary component's surface, we have four parameters: the longitude λ_{s} and the latitude β_{s} of the center, the radius r_{s} and the brightness ratio br_{s} to the normal brightness. All other parameters were determined by the analysis: the fill-out ratio f of both components or the fractional radii (side) r_1 and r_2 of the primary and secondary components, the orbital inclination i, one of the fractional luminosities l_1 and $l_2(= 1 - l_1)$ and four spot parameters λ_{s}, β_{s}, r_{s} and br_{s}.

We determined these parameters so that the $(O - C)^2 = \sum(l_{\mathrm{obs},j} - l_{\mathrm{th},j})^2$ values should be minimum for the V light curve. The actual calculations were made by dividing the surfaces of the primary and the secondary components into 26896 and 15376 elements, respectively. The derived preliminary photometric parameters are listed in Table 3. The theoretical light curves based on these system parameters are shown with solid lines in Fig.3 for V observations. Fig.4 display the equatorial configurations of the components represented by the parameters in Table 3 together with the critical Roche lobes corresponding to the mass ratio $q = 0.305$.

5. Absolute Quantities

Now, we calculate absolute values for the physical quantities for V376 And. Rucinski (2001) reported that the semi-amplitudes of radial velocities of both components are $K_1 = 70.00$ km/s and $K_2 = 229.6$ km/s, which directly give the mass ratio $q = 0.305$ employed in our study, and also deduced another orbital element as $(M_1 + M_2)\sin^3 i = 2.232 \pm 0.055\ M_{\odot}$. Combining the orbital elements of Rucinski (2001) with the photometric elements (Table 3) obtained in our study, we obtained the masses of the components as $M_1 = 2.5\ M_{\odot}$ for the primary and $M_2 = 0.76\ M_{\odot}$ for the secondary as well as the radii of the components as $R_1 = 2.9\ R_{\odot}$ and $R_2 = 1.8\ R_{\odot}$.

6. Discussion

Using the maximum magnitude and the HIPPARCOS parallax data of V376 And, Rucinski (2001) derived the absolute magnitude of the combined light of both components as $M_V = 0.85 \pm 0.40$, which is consistent with $M_V = 1.1$ obtained from the period-luminosity-color relation for W UMa type binaries. Applying the bolometric correction $BC = -0.17$ for an A4V star (Cox, 2000) to $M_V = 0.85 \pm 0.40$, and also combining this absolute magnitude with $l_1 = 0.866$ in table 3 and $R_1 = 2.9\ R_{\odot}$ in table 4, we obtain the effective temperature of the primary component as $T_{\mathrm{eff},1} = 8470$ K. This is in good agreement with the effective temperature of A4V stars (e.g., Cox 2000).

Next, we consider what produces such a significant light curve asymmetry as displayed in Fig.1. It is noted that there is no appreciable difference among the light curves of HIPPARCOS (ESA 1997), Dumitrescu et al. (2005) and our study. This suggests that the shape of the light curve has been stable for at least 15 years. In our preliminary analysis, we began by analyzing the first half of light curve (including Max I [= brighter maximum]) and the second half of that (including Max II), separately, to have an idea which maximum has been less disturbed by unusual brightness distribution over both components' surface. We found that a $(O - C)^2$ value for the first half of light curve is a little smaller than the second half, suggesting that the second half would be affected by an existence of the dark region on one or both components' surface. On the other hand, as found in table 3, the fractional luminosity of the secondary component is only $l_2 = 0.134$. Thus, the secondary component seems too faint to produce the magnitude difference between Max I and

Table 4 Absolute quantities of V376 And.

Masses	M_1, M_2	2.5 $M_{\odot}$, 0.76 $M_{\odot}$
Radii (side)	R_1, R_2	2.9 $R_{\odot}$, 1.8 $R_{\odot}$
Absolute magnitudes	$M_{V,1}$, $M_{V,2}$	+1.01, +3.03

Max II up to $\Delta V \sim 0.08$ mag, which corresponds to $\Delta l \sim 0.08$. Therefore, we hypothesized that the primary (hotter) component has a dark spot on its trailing side surface.

The primary component of V376 And is regarded as too hot to have a convective envelope, which is considered necessary to develop dark spots on the surface due to stellar activity. In fact, as mentioned above, the light curve asymmetry of V376 And has not shown any appreciable variation which is expected in stellar activity cases. Thus, the dark spot introduced as our working hypothesis should not be associated with any stellar activity as often found among eclipsing binaries with cool components.

Even so, the observed light curve asymmetry tells us that there exist some other kind of dark region (represented by the dark spot in our preliminary analysis) on the surface of the primary component of V376 And. Therefore, it is very desirable to make extensive spectroscopic and photometric observations of V376 And to reveal the cause of the light curve asymmetry.

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