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THE NATURE OF THE BRIGHT EARLY-TYPE ECLIPSING BINARY THETA 1 Ori A = V1016 ORIONIS

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The bright (V = 6.7) westernmost member of the Trapezium, θ^1 Ori A (41 Ori A, HR 1893, HD 37020, V1016 Ori) is a long-period eclipsing binary with magnitude-deep declines (Lohsen 1975). Despite the brightness of the system, uncertainty surrounds the nature of the secondary component, which is most probably a pre-main-sequence star (Stickland & Lloyd 2000). The purpose of this note is to highlight some new observations that could clarify the issue. Most of the observational difficulty with this system stems from the unusually long period for an eclipsing system of 65.43 days, resolved by Baldwin (1976). The primary eclipse is too long to observe continuously in one night (FWHM $\sim$ 10 hours), but it occupies barely one per cent of the cycle, and in an observing season there may be only three cycles. As a consequence, the light curve of the primary eclipse is composed of a series of sections covering only parts of the eclipse, ingress, egress or the central part of the minimum. The most complete eclipses are those of Lohsen (1976) and more recently, Vitrichenko (1998), and visually by the AAVSO (Mattei 1977). Multi-colour photometry shows very little change in colour during the primary eclipse.

Spectroscopically the system is well, if not particularly accurately, observed and several orbital solutions have been published, most recently by Stickland & Lloyd (2000), who provide a detailed review of all the radial velocity data. The system is quite eccentric, with $e = 0.624$ and the secondary eclipse occurs at photometric phase 0.130 ± 0.015. The uncertainty on the time of secondary eclipse corresponds to ± 1.0 days. It is likely that none of the published spectroscopic or photometric observations, even the visual ones, have been made during the secondary eclipse.

A range of spectral types from O8 – B3 have been given for the primary with the majority around very early B type. Stickland & Lloyd (2000) give B1V from the cross correlation of ultraviolet spectra while Vitrichenko et al. (1998) give B0V on the basis of an adopted temperature of $T_1 = 30\,000$ K derived from the photometry. There is no convincing spectroscopic signature of the secondary component, even at primary minimum (Vitrichenko et al. 1998), which implies that the secondary component is at least 2–3 magnitudes fainter than the primary. However, observations in the near infrared show an excess over and above what is expected for an early B-type star Vitrichenko (1999). Attempts to model the system have not led to any clear consensus. Bossi et al. (1989) could not model the system with main-sequence stars and suggested a B3III–IV primary component with a pre-main-sequence secondary. Vitrichenko (1998, 1999) used a star-dust model to fit the light curve and the optical-to-infrared colours, with components of B0–0.5V and B8–A0V, a dust shell at a temperature of T_D = 1600 K and a separate infrared source. A recurring theme in many of the analyses is the pre-main-sequence nature of the secondary component.

Table 1. Times of primary minimum of θ^1 Ori A

JD	$O-C$ (days)	Note	Reference
2436863.073	0.003	1	Strand 1975
2441966.813	−0.015	2, 11	Lohsen 1975
2441966.827	−0.001	3	Lohsen 1976
2442359.421	−0.004	3	Lohsen 1976
2442751.946	−0.076	4, 11	Walker 1976
2442752.015	−0.007	3	Lohsen 1976
2442752.010	−0.012	5	Caton et al. 1977
2442817.545	0.090	6, 11	Baldwin 1976
2443144.613	−0.006	2, 7	Mattei 1977
2443144.639	0.020	8	Walker 1977
2443210.033	−0.019	9	Franz 1977
2443537.235	0.019	2	Zakirov 1979
2444191.552	0.008	10	Sowell & Hall 1982
2450080.494	−0.002	2	Agerer & Huebscher 1997

Notes: 1. Mean of timings from two photographic magnitudes $\sigma \sim 0.04$ days. 2. Observed minimum. 3. Observations from three minima used to construct a complete minimum. The times of minima are derived from Lohsen's ephemeris. 4. Two isolated observations very close to minimum. 5. Timing derived from a major part of an ingress, $\sigma \sim 0.01$ days. 6. Isolated visual observation during the eclipse. 7. Timing derived from the faintest visual observations of six consecutive minima. 8. Timing derived from a major part of an egress, $\sigma \sim 0.01$ days. 9. Timing derived from part of an egress, $\sigma \sim 0.01$ days. 10. Time of minimum derived by Sowell & Hall from a major part of an egress. 11. Not used in the solution.

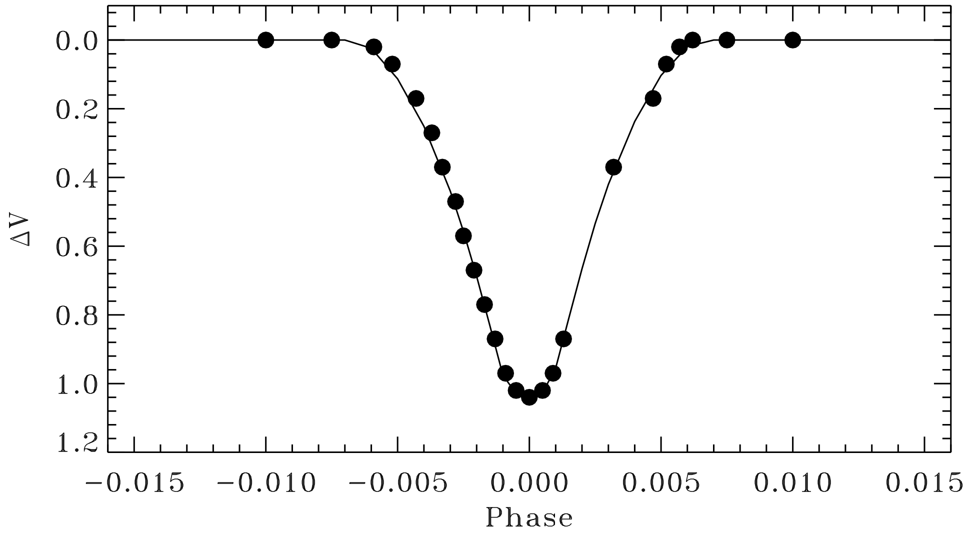

Figure 1. The light curve of θ^1 Ori A around primary minimum showing the normal points derived from Lohsen (1976) and the solution with $T_2 = 9\,000$ K from Table 2 over plotted.

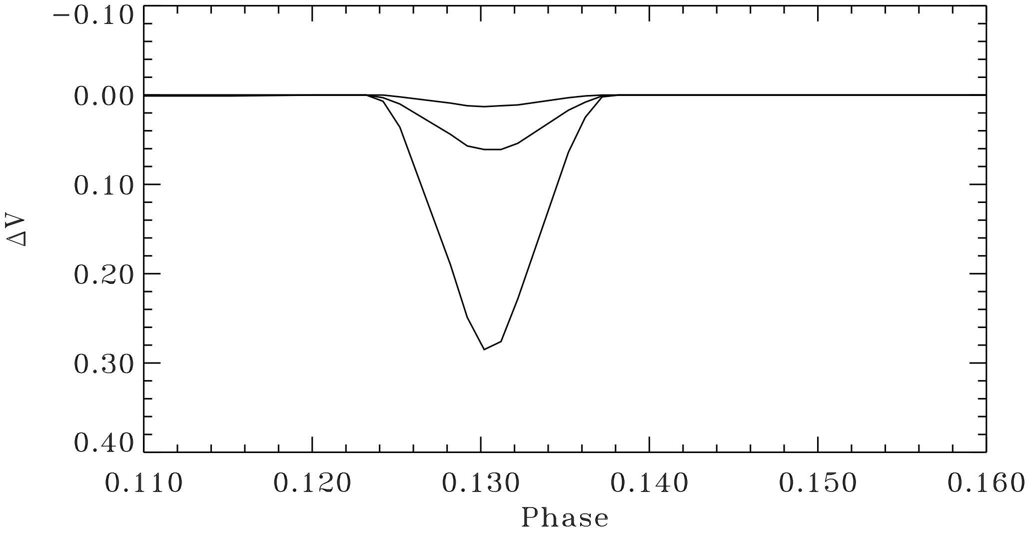

Figure 2. The modelled light curve around secondary minimum showing the decreasing visibility of the eclipse with decreasing temperature of the secondary component.

To determine an accurate ephemeris the times of minimum have been derived from all the published eclipse observations but in practice this is not simple as the eclipse is composed of fragments. Observations around the deepest part of minimum do not necessarily provide the best timing as the light curve is rather flat, with $\Delta V < 0.1$ mag over 4 hours, and the observations are invariably noisier than at other times. Only Lohsen (1976) and Vitrichenko (1998) have sufficient observations to claim complete coverage of the eclipse and even these have some significant gaps. The fragments of light curve have been phased with respect to the adopted shape of the minimum from Lohsen (1976) and the times of primary minimum are given in Table 1. The derived ephemeris is

$$\mathrm{JD_{MinI}} = 2442752.022\ (\pm\, 0.004) + 65.43280\ (\pm\, 0.00008) \times E.$$

The LIGHT2 code (Hill et al. 1989) has been used to model the system with a series of evenly sampled normal points, where there are sufficient observations, derived from the light curve of Lohsen (1976) (see Figure 1). In the LIGHT2 solutions the temperature of the primary has been fixed at 26 000 K, which is appropriate for a B1V star. Not surprisingly, given the lack of a secondary eclipse, the temperature of the secondary component is essentially undefined and its radius is also poorly determined (see Table 2). However, this result conceals two types of solution. At lower temperatures, $T_2 < 12\,000$ K, the radius of the primary is larger than the secondary but at higher temperatures the relative sizes of the components is reversed. The details are given in Table 2. Two solutions with the temperature of the secondary fixed at $T_2 = 6\,000$ K and 9 000 K are essentially identical.

Assuming a mass appropriate for a B1V star, $M_1 = 12\,\mathrm{M}_\odot$, and taking $K = 33\ \mathrm{km\,s^{-1}}$ from the orbital solution, gives $R_1 = 6.6\,\mathrm{R}_\odot$, $M_2 = 3.0\,\mathrm{M}_\odot$, and $R_2 = 5.2\,\mathrm{R}_\odot$. The radius of the primary is consistent with the radius of a B1V star, and, by definition, so are the mass and temperature. However, the secondary mass of $3.0\,\mathrm{M}_\odot$ corresponds to a main-sequence star of spectral type near A0, but the radius of $5.2\,\mathrm{R}_\odot$ is more appropriate for an early–mid B-type star. Clearly the secondary is not a main-sequence star and from evolutionary arguments Stickland & Lloyd conclude that it is most likely a pre-main-sequence star. For the solutions with a higher temperature secondary, the radius of the primary is too small for a B1V star, implying that it is either of later spectral type, so cooler and less massive, or some physically unrealistic object. The radius of the secondary is too large, by a factor of two, for a mid B-type star, so this component must either be of earlier spectral type, so hotter and more massive, or evolved. Therefore, it does not seem possible to construct a realistic model with the hotter, $T_2 = 15\,000$ K, secondary.

Table 2. Solutions to the light curve with $T_1 = 26\,000$ K.

T_2 (K)	R_1/a	R_2/a	i (deg)	R_1 ($R_\odot$)	R_2 ($R_\odot$)
$7\,300 \pm 14\,500$	0.0307 ± 0.0005	0.0240 ± 0.0035	89.6 ± 0.3	6.6	5.2
6 000	0.0308 ± 0.0003	0.0239 ± 0.0011	89.6 ± 0.3	6.7	5.2
9 000	0.0307 ± 0.0003	0.0244 ± 0.0008	89.7 ± 0.3	6.6	5.3
15 000	0.0244 ± 0.0006	0.0302 ± 0.0014	89.6 ± 0.2	5.3	6.5

The light curves around secondary eclipse for the three fixed-temperature solutions in Table 2 are shown in Figure 2 and it is clear that observations of this eclipse would largely resolve the issue. The high-temperature secondary solution could easily be eliminated and with careful observation it should at least be possible to place a reliable upper limit on the depth of the eclipse, and with it, the temperature of the secondary. An ephemeris for the current observing season is given in Table 3 and observations of both primary and secondary minimum, covering the period of uncertainty, are encouraged.

Table 3. Ephemeris of θ^1 Ori A for the current observing season.

JD	Date UT			
2451520.017	1999	12	7.517	MinI
2451528.6 ± 1.0	1999	12	16.1	MinII
2451585.450	2000	2	10.950	MinI
2451594.0 ± 1.0	2000	2	19.5	MinII
2451650.883	2000	4	16.383	MinI
2451659.4 ± 1.0	2000	4	24.9	MinII

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