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THE ESCAPING SPECTROSCOPIC BINARY θ^1 ORI E

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RESUMEN

Recientemente, Costero et al. (2006) descubrieron que θ^1 Ori E es binaria espectroscópica de líneas dobles. Del análisis de 86 espectros Echelle obtenidos en un lapso de tres años, en los que los sistemas de ambas componentes son separables, encontramos que sus tipos espectrales son casi idénticos entre sí y similares a los de estrellas subgigantes de tipo G temprano o intermedio, con Li I λ 6708 Å en fuerte absorción y la línea K del Ca II en moderada emisión. La presencia de estas líneas es indicativa de que la binaria se encuentra en la etapa de pre-secuencia principal y, por lo tanto, de su pertenencia al Cúmulo de la Nebulosa de Orión (ONC). Las curvas de velocidad radial de las dos componentes muestran que la órbita de la binaria es circular ($e < 10^{-3}$) y de periodo 9.8952 ± 0.0007 d; las semiamplitudes son casi idénticas (84.4 ± 1.0 km s^{-1}) en ambas componentes y la velocidad sistémica es de 34.3 ± 0.7 km s^{-1}. Esta última es 8.3 km s^{-1} mayor, por al menos 3σ, que la velocidad radial promedio de los miembros del ONC, y muy similar a la velocidad transversal –relativa a la componente A del Trapecio– obtenida por Allen et al. (2004) y Sánchez et al. (2008) para la estrella. Concluimos que la binaria está escapando del cúmulo donde se formó.

ABSTRACT

θ^1 Ori E was found to be a double-lined spectroscopic binary by Costero et al. (2006). From the analysis of 86 Echelle spectra obtained during three years, in which the systems of both components are separable, we found that the nearly identical spectra are consistent with both stars being early- to mid-G subgiant stars, with strong Li I λ 6708 Å absorption and moderate emission Ca II K lines. The latter features are indicative of the pre-main-sequence evolutionary stage of the binary and, hence, of its membership to the Orion Nebula Cluster (ONC). The radial velocitiy curves of both components yield a circular orbit ($e < 10^{-3}$) for the binary, with a period of 9.8952 ± 0.0007 d. The semi-amplitudes of the curves are almost identical (84.4 ± 1.0 km s^{-1}) and the systemic velocity is 34.3 ± 0.7 km s^{-1}. The latter value is 8.3 km s^{-1} larger, by at least 3σ, than the average radial velocity of the ONC members, and very similar to the transverse velocity (relative to component A in the Trapezium) derived for the star by Allen et al. (2004) and Sánchez et al. (2008). We conclude that the binary is escaping from the cluster in which it was formed.

Key Words: binaries: individual ($\boldsymbol{\theta^1}$ Ori E) — binaries: spectroscopic — stars: kinematics — stars: pre–main sequence

1. INTRODUCTION

θ^1 Ori E, the "fifth" member of the Orion Trapezium, has many other names frequently used in the literature, including Brun 584, ADS 4186 E, Parenago 1864 and NSV 2291. Identification charts for this and other members of the Trapezium can be found elsewhere (e.g. Wolf 1994; Herbig & Griffin 2006). Its proximity to the ~ 3.5 mag brighter component A in the Trapezium ($\sim 4''$) has complicated the study of component E in the past. Indeed, the scarce published optical photometric data for θ^1 Ori E are probably contaminated by the neighboring component A. Published infrared PSF photometry data are probably more reliable (e.g. McCaughrean & Stauffer 1994; Petr et al. 1998; Muench et al. 2002; Lada et al. 2004). The star is a non-thermal, variable radio source (e.g. Felli et al. 1993), and one of the brightest and also variable X-ray sources in the Trapezium cluster (Stelzer et al. 2005).

Allen, Poveda, & Worley (1974) first noticed that θ^1 Ori E might be separating from component A in the Trapezium. Taking advantage of more recent astrometric data, Allen, Poveda, & Hernández-Alcántara (2004) confirmed the relative proper motion trend. Since no radial velocity was published for the star, we obtained Echelle spectra of the object. It was found that θ^1 Ori E (Costero et al. 2006) is a double-lined spectroscopic binary, with nearly identical components and an orbital period of around 10 days. Shortly afterwards, Herbig & Griffin (2006) published orbital parameters of the binary based on

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10 high-dispersion spectra obtained during a time-interval of 7 years. The small but significant differences between their results and those derived from our data –in particular the one related to the systemic velocity of the binary– stimulated us to continue the spectral study of the binary. Here we report partial results derived from Echelle spectra obtained as described in § 2. In § 3 we present some relevant results from the spectral analysis and radial velocity measurements, and in § 4 we compare the kinematics of the binary with that of the cluster members.

2. OBSERVATIONS

Echelle spectra of θ^1 Ori E were obtained with the *REOSC* spectrograph attached to the 2.1 m Telescope of the Observatorio Astronómico Nacional at San Pedro Mártir, Baja California. Most of them were taken with the 1024×1024 SITe 3 CCD, yielding spectral resolution $R \sim 12,000$ (2.3 pixels, 24 μm each). During the observing nights of 2006 January 6–13 the Thomson 2048×2048 CCD was used, with spectral resolution $R{\sim}17{,}000$ (2.5 pixels, 15 μm each). Additionally, the nearby Trapezium component A was observed at least once every night. All the observations were carried out with the 300 l/mm cross-disperser, blazed at around 5500 Å in its first dispersion order. The data were reduced using standard IRAF routines for Echelle CCD spectroscopy.

A summary of the observations is presented in Table 1, where the first and second columns list the date interval of each observing run and the corresponding spectral range, while the third column gives the total number of spectra obtained during those nights. The last column lists the number of spectra actually used in deriving the orbital parameters of the binary, as described in § 3. The spectra in which the line-systems of both components are blended –and not used in the orbital calculations– were obtained during the nights of 2004 Oct. 7 and Dec. 10; 2006 Jan. 10, part of 11 and 15, and Dec. 8; 2007 Sep. 6; and 2008 Jan. 12.

TABLE 1

OBSERVING LOG

Date	Range (Å)	Spectra	Used
2004 Oct 6–8	3800–6880	3	2
2004 Oct 16	3640–6870	2	2
2004 Dec 10–14	3620–6860	10	9
2006 Jan 8–13	3720–7340	64	36
2006 Jan 15–17	3860–7090	8	7
2006 Feb 25	4070–7320	2	2
2006 Mar 13,14	3880–7090	6	6
2006 Dec 7–12	3860–6880	20	8
2007 Sep 6–9	3800–6880	8	6
2007 Nov 22,23	3800–6880	2	2
2008 Jan 11–19	4000–7090	7	6

3. RESULTS

The spectra of θ^1 Ori E clearly show that the star is a double-lined binary, with components of nearly identical spectral-type. The average of the three spectra obtained when the binary was closest to conjunction (2006 Dec. 8) was compared with suitable MK spectral standards –from the lists by Morgan & Keenan (1973), Morgan, Abt, & Topscott (1978) and Torres-Dodgen & Weaver (1993)– acquired with the same instrument, and also with synthetic spectra. The composite spectrum shows a strong G-band and neutral metallic lines. The Balmer H I lines are masked by the much stronger nebular lines, which precludes an easy and fast spectral classification. By comparing lines arising from ionized metals (e.g. Fe II and Sc II) with those of neutral atoms, and using several luminosity-sensitive lines, we conclude that the combined spectrum of both components in θ^1 Ori E is compatible with a G0 IV to G5 III star, with highest likelihood around G2 IV.

Parenago (1954) assigned θ^1 Ori E a high membership probability to the ONC, on the basis of proper motion arguments. Three features in the spectra of the star further support its membership to the young cluster:

(1) In those spectra obtained when the binary was near quadrature (and hence, where the two stellar systems were well separated), the Ca II K resonance line showed a moderate double emission superimposed on a broad, blended absorption. Within errors, these emission lines were shifted with the same radial velocities as those measured –on the same spectra– in the absorption-line systems of the binary components, as described below. The presence of Ca II in emission is indicative of chromospheric activity, typically found in very young stars.

(2) Between the Ca II K emission lines, the interstellar component is clearly visible; its equivalent width is only slightly smaller ($\sim$ 10%) than that measured in the spectrum of the much hotter and brighter nearby component A in the Trapezium. The Na I D_1 and D_2 stellar lines show no emission, but the corresponding interstellar components are also slightly weaker than those in θ^1 Ori A. It has been

TABLE 2

SPECTROSCOPIC ORBITAL PARAMETERS OF θ^1 ORI E

Parameter	Value (3σ error)
$P_{\rm orb}$ (days)	9.89520±0.00069
γ (km s^{-1})	34.3±0.7
K_1 (km s^{-1})	84.2±1.2
K_2 (km s^{-1})	84.6±1.3
HJD$_{\rm o}$ (2453280 +)	53281.039±0.017
$q = M_2/M_1$	1.004±0.018

well established (see e.g. O'Dell 2001a,b) that most of the (patchy) absorbing interstellar dust in the direction of the ONC is located in front of and near the visible stars in the cluster, and that the cluster far side is immersed in the dense, highly opaque Orion molecular cloud. Hence, the similarity between the interstellar lines in θ^1 Ori E and θ^1 Ori A implies that both stars are located between the foreground dust clouds and the background molecular cloud, all at a similar distance from us.

(3) The Li I λ 6708 Å line is very strong in the spectra of the two binary components. Assuming equal luminosity for both stars, the corrected line equivalent width is about 0.3 Å in each component. Strong Li absorption is also a compelling indication of the object's youth.

Radial velocities of the binary components of θ^1 Ori E were measured in the 86 spectra in which both binary components are deblended. Using the IRAF routine *fxcor* in the $\lambda\lambda$5120–5515 Å spectral interval, we cross-correlated those spectra with that of β Vir –an *IAU CORAVEL* radial velocity standard and an F9 V spectral standard in Morgan & Keenan (1973)– obtained with the same instrument.

We determined the orbital parameters from the measured radial velocities of both components and found that the orbital eccentricity ($e < 10^{-3}$) is smaller than the error of the fitted soluttions. Hence, we have assumed a circular orbit by fitting the data to sinusoids of the form

$$V(t) = \gamma + K \ \sin\left[2\pi(t - {\rm HJD_o})/{\rm P_{orb}}\right] ,$$

through a least-squares algorithm. Since the solutions are very similar for both line-systems, we have adopted the simultaneous solution for the two stars. The results are listed in Table 2. The measured heliocentric velocities are plotted in Figure 1, where the data have been folded with the derived orbital period and zero phase. The latter corresponds to the inferior conjunction of component labeled as Star 2.

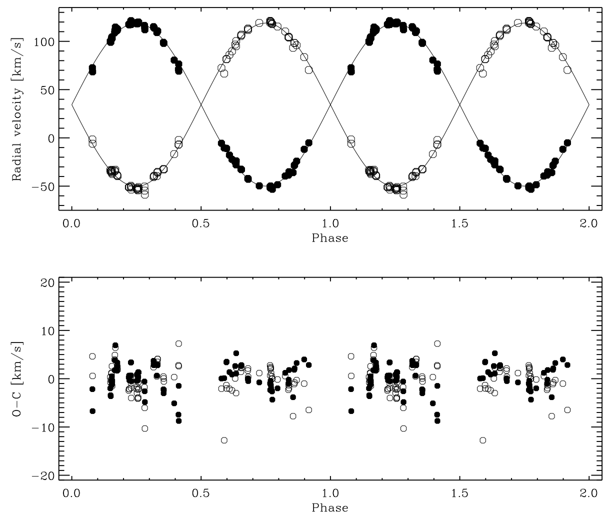

Fig. 1. Radial velocity curves of θ^1 Ori E, folded with the orbital parameters given in Table 2 (top panel) and their residual velocities (lower panel). Filled and open circles correspond to components labeled 1 and 2, respectively.

4. DISCUSSION

The systemic velocity we obtained for θ^1 Ori E (γ =34.3 km s^{-1}) is large compared to the mean radial velocity of the ONC members. Sicilia-Agilar et al. (2005) measured the radial velocities of 133 ONC members. For the brightest 79 stars in their sample –located in the central (15′) part of ONC– they obtained a mean heliocentric radial velocity of 26 km s^{-1} and a dispersion $\sigma_r = 1.8$ km s^{-1}. Complementary to this work, the recent survey by Fűrész et al. (2008) covers a much larger field (2.7°×1.5°) that includes the ONC and the Orion 1c association. From the radial velocities of 1215 stars (most derived from only one spectrum), the latter authors find the same mean radial velocity as Sicilia-Agilar et al. (2005), but a larger $\sigma_r = 3.1$ km s^{-1}. It should be mentioned that Fűrész et al. (2008) find a substantial north-south velocity gradient and possible dynamical sub-groups in their extended sample, circumstances that –together with the probable intrusion of unrecognized spectroscopic binaries– broaden the observed velocity distribution. The γ velocity we obtain for θ^1 Ori E is 8.3 km s^{-1} larger than the mean radial velocity found by Sicilia-Agilar et al. (2005) and Fűrész et al. (2008). Such peculiar radial velocity amounts, respectively, to about 4.6 and 2.7 times the velocity dispersion obtained by these authors for the ONC members.

In addition, Allen et al. (1974) first noticed that the angular separation between θ^1 Ori E and θ^1 Ori A increases secularly, a trend confirmed by Allen et al. (2004). In this meeting, Sánchez et al. (2008) presented precise astrometric measurements of archival short-exposure HST images of the Orion Trapezium. Based on these and previous visual astrometry, the latter authors conclude that components E and A are separating from each other at a rate of 3.5 ± 0.5 mas yr^{-1}. At 414 pc, the very precise distance to the ONC recently derived by Menten et al. (2007), the corresponding angular separation rate is 7.0 ± 1.1 km s^{-1}. This relative velocity is, respectively, 5.0 and 3.2 times larger than the transverse velocity dispersion found by van Altena et al. (1988) ($\sigma_t = 1.4 \pm 0.1$ km s^{-1}) and by Jones & Walker (1988) ($\sigma_t = 2.2 \pm 0.25$ km s^{-1}) for the ONC members, when assuming a distance of 414 pc to the cluster.

The peculiar kinematics of θ^1 Ori E has two possible interpretations: either the binary star does not belong to the ONC, or it is a cluster member moving with a spatial velocity –relative to the cluster– of nearly 11 km s^{-1}. From the arguments given in § 3 and those thoroughly exposed by Herbig & Griffin (2006), θ^1 Ori E is almost certainly a member of the ONC, unless extreme *ad hoc* peculiarities are invoked for the star.

We adopt the second, more feasible interpretation given above, and conclude that θ^1 Ori E is escaping from the young cluster in which it formed. Its spatial velocity, at least 3σ larger than the velocity dispersion of the cluster stars, suggests that the kinematics of the θ^1 Ori E system is not the result of a classical 2-body relaxation process, but rather the effect of few body strong interaction, similar to those producing runaway stars (Poveda, Ruiz, & Allen 1967; Rodríguez et al. 2005).

Moreover, the membership θ^1 Ori E to the Orion Trapezium has also been established by Allen et al. (2004). We estimate the escape velocity from the bright Trapezium stars to be 6 km s^{-1}, nearly half the relative space velocity of θ^1 Ori E. So, if formed within the Trapezium, the binary star is escaping from this massive multiple system.

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