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*Letter to the Editor*

# Bispectrum speckle interferometry of the Orion Trapezium stars: detection of a close (33 mas) companion of $\Theta^1\mathrm{Ori\,C}$ [⋆]

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**Abstract.** We present bispectrum speckle interferometry observations with the SAO 6 m telescope of the four brightest stars in the Orion Trapezium. Diffraction-limited images with an unprecedented resolution $\lambda/D$ of 57 mas and 76 mas were obtained in the $H$- and $K$-band, respectively. The $H$ and $K$ images of $\Theta^1\mathrm{Ori\,C}$ (the star responsible for the proplyds) show for the first time that $\Theta^1\mathrm{Ori\,C}$ is a close binary with a separation of only $\sim 33$ mas ($H$-band observation). The sub-arcsecond companions of $\Theta^1\mathrm{Ori\,A}$ and $\Theta^1\mathrm{Ori\,B}$ reported by Petr et al. (1998) are confirmed. We use the magnitudes and colors of the companions to derive information about their stellar properties from the HR-diagram. In addition we briefly discuss the multiplicity of the Trapezium stars. Considering both, the visual and the spectroscopic companions of the 4 Trapezium stars, there are at least 7 companions, i.e. at least 1.75 companions per primary on average. This number is clearly higher than that found for the low-mass stars in the Orion Nebula cluster as well as in the field population. This suggests that a different mechanism is at work in the formation of high-mass multiple systems in the dense Trapezium cluster than for low-mass stars.

**Key words:** techniques: interferometric – stars: individual: $\Theta^1\mathrm{Ori\,C}$; $\Theta^1\mathrm{Ori\,A}$; $\Theta^1\mathrm{Ori\,B}$ – stars: pre-main sequence – stars: binaries: close

## 1. Introduction

The Orion Nebula cluster is one of the most prominent and nearby ($D \sim 450\,\mathrm{pc}$) star forming regions (for a review see Genzel & Stutzki 1989). Its core contains a very dense cluster of young ($\lesssim 1 \times 10^6$ yr) stars (cf. Herbig & Terndrup 1986; McCaughrean & Stauffer 1994; Hillenbrand 1997). The Trapezium ($\Theta^1\mathrm{Ori\,ABCD}$), the system of the four most massive and luminous O-type and early B-type stars, is located in the center of the cluster. The strong stellar wind and the ionizing radiation of $\Theta^1\mathrm{Ori\,C}$ has strong effects on the surrounding cloud material (Bally et al. 1998; see also Richling & Yorke 1998).

Petr et al. (1998; P98 hereafter) presented the results of 130 mas resolution near-infrared speckle holographic observations of the Trapezium cluster core, in which they could detect sub-arcsecond companions of the two Trapezium stars $\Theta^1\mathrm{Ori\,A}$ and $\Theta^1\mathrm{Ori\,B}$. Simon et al. (1999) reported the detection of an additional, very faint companion of $\Theta^1\mathrm{Ori\,B}$. In this paper we present the first near-infrared bispectrum speckle interferometry observations with diffraction-limited resolution of 57 mas in the $H$-band and 76 mas in the $K$-band.

## 2. Speckle observations and results

The speckle interferograms of $\Theta^1\mathrm{Ori}$ A, B, C, and D were obtained with the 6 m telescope at the Special Astrophysical Observatory (SAO) in Russia on Oct. 14, 1997 ($H$-band) and Nov. 3, 1998 ($K$-band). Diffraction-limited images were reconstructed from the speckle data using the bispectrum speckle interferometry method (Weigelt 1977; Lohmann et al. 1983). The modulus of the object Fourier transform was determined with the speckle interferometry method (Labeyrie 1970). The speckle transfer functions were derived from speckle interferograms of the unresolved star $\Theta^1\mathrm{Ori\,E}$. Figs. 1 and 2 show the power spectra and images of $\Theta^1\mathrm{Ori}$ A, B, and C. The observational parameters and the properties of the resolved stars are summarized in Table 1. The flux ratios were determined by fitting cosine functions to the power spectra.

*$\Theta^1 Ori\,A$:* The companion $\mathrm{A}_2$ of the primary star $\Theta^1\mathrm{Ori\,A}_1$ (detected by P98) is clearly visible in our images.

*$\Theta^1 Ori\,B$:* The two companions $\Theta^1\mathrm{Ori\,B}_{2,3}$ are clearly resolved, confirming the detection by P98. In our images we cannot see the new faint component detected by Simon et al. (1999) because it is just below our detection limit.

*$\Theta^1 Ori\,C$:* Our power spectra and images of $\Theta^1\mathrm{Ori\,C}$ show a companion $\mathrm{C}_2$ with a separation of $(33 \pm 5)$ mas from the pri-

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[⋆] Based on data collected at the SAO 6 m telescope in Russia.

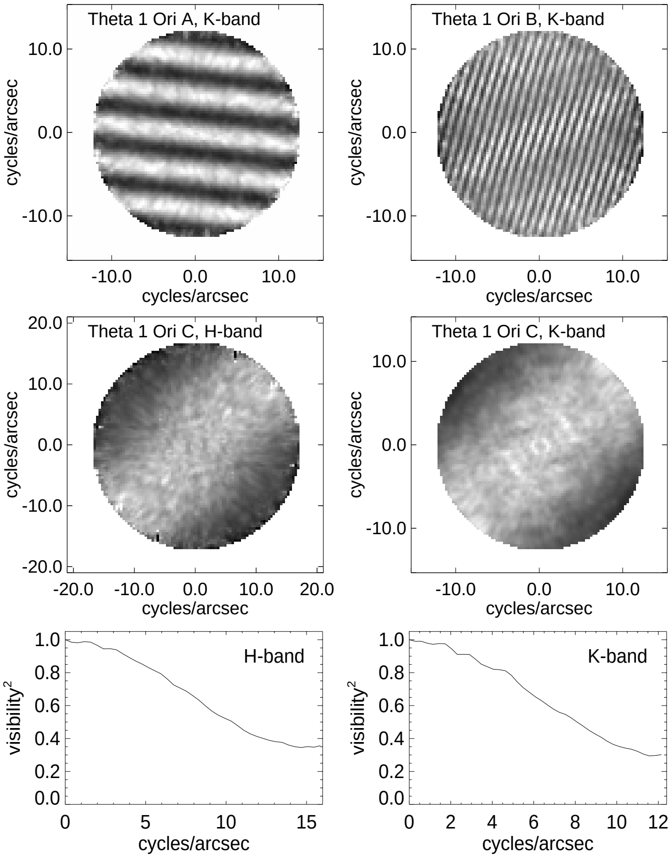

**Fig. 1.** Top: Reconstructed power spectra of $\Theta^1$Ori A, B, and C; Bottom: Line plots of the power spectra of $\Theta^1$Ori C perpendicular to the fringe direction.

mary $C_1$ ($H$-band; see Table 1). This is the first detection of a companion of $\Theta^1$Ori C.

$\Theta^1 Ori\,D$*:* We find no indication for a companion of D.

From the average surface density of stars in the Trapezium cluster reported by Simon et al. (1999) we estimate that the probability of finding a star with $K < 10$ within $1''$ from a given position is $< 1\%$. This suggests that the visual companions we observe actually are companions of the respective primaries and not only chance projections of unrelated stars.

## 3. Stellar properties of the companions

In order to obtain information about the physical properties of the companions from our speckle results, we have used the photometric and spectroscopic data and stellar parameters compiled by Hillenbrand (1997) and Hillenbrand et al. (1998). From the known system magnitudes and the flux ratios determined in the speckle images we have computed the $K$-band magnitudes and the $H-K$ colors of the speckle companions. These data can be used to estimate the luminosity and the effective temperature of the stars: the $K$-band magnitude yields the stellar luminosity as a function of the stellar temperature (using the compilation of intrinsic $V-K$ colors and bolometric corrections of Kenyon & Hartmann 1995), and the $H-K$ color can be transformed into the stellar temperature. The resulting parameters can then be employed to estimate stellar masses and ages (cf. Fig. 3 and Table 2).

**Table 1.** Observational parameters and results:
$H$-band: Nicmos3 camera, $\lambda_c/\Delta\lambda = 1613/304$ nm, $600 \times 150$ ms- exposures, seeing $\sim 1.6''$, scale 19.70 mas/pixel;
$K$-band: Hawaii-array camera, $\lambda_c/\Delta\lambda = 2160/320$ nm for A and B, 2200/200 nm for C, $600 \times 120$ ms-exposures, seeing $\sim 1.8''$, scale 27.00 mas/pixel.

| $\Theta^1$ Ori | Sep. [mas] | Pos. Angle [deg.] | Flux ratio |
|---|---|---|---|
| | *$H$-band observations (epoch 14 Oct. 1997):* | | |
| $B_1B_2$ | $942 \pm 20$ | $254.9 \pm 1$ | $0.12 \pm 0.02$ |
| $B_1B_3$ | $1018 \pm 20$ | $250.0 \pm 1$ | $0.06 \pm 0.03$ |
| $B_2B_3$ | $114 \pm 5$ | $204.3 \pm 4$ | $0.40 \pm 0.04$ |
| $C_1C_2$ | $33 \pm 5$ | $226 \pm 6$ | $0.26 \pm 0.02$ |
| | *$K$-band observations (epoch 03 Nov. 1998):* | | |
| $A_1A_2$ | $221 \pm 5$ | $353.8 \pm 2$ | $0.25 \pm 0.01$ |
| $B_1B_2$ | $942 \pm 20$ | $254.4 \pm 1$ | $0.30 \pm 0.02$ |
| $B_1B_3$ | $1023 \pm 20$ | $249.5 \pm 1$ | $0.10 \pm 0.03$ |
| $B_2B_3$ | $117 \pm 5$ | $205.7 \pm 4$ | $0.32 \pm 0.05$ |
| $C_1C_2$ | $37 \pm 6$ | $222 \pm 5$ | $0.32 \pm 0.03$ |

**Table 2.** Companions of the Trapezium stars ($M_p$: primary mass, $M_s$: secondary mass, $\rho$: distance). References: 1: this work; 2: P98; 3: Bossi et al. (1989); 4: Simon et al. (1999); 5: Abt et al. (1991)

| Primary $\Theta^1$ Ori | $M_p$ $[M_\odot]$ | Comp. | $\rho$ [AU] | $M_s/M_p$ | Ref. |
|---|---|---|---|---|---|
| $A_1$ | 20 | $A_2$ (vis) | 100 | $\sim 0.2$ | 1,2 |
| | | $A_3$ (spec) | 1 | $\sim 0.13$ | 3 |
| $B_1$ | 7 | $B_2$ (vis) | 430 | $< 0.7$ | 1 |
| | | $B_3$ (vis) | 460 | $< 0.5$ | 1 |
| | | $B_4$ (vis) | 260 | $< 0.3$ | 4 |
| | | $B_5$ (spec) | 0.13 | | 5 |
| $C_1$ | 45 | $C_2$ (vis) | 16 | $< 0.13$ | 1 |
| D | 17 | apparently single | | | |

For $\Theta^1$Ori $C_2$ we find $K = 5.95 \pm 0.11$ and $H-K = 0.24 \pm 0.10$. Since the extinction[1] of $A_V = 1.8$ corresponds to $E(H-K) = 0.11$ (cf. Rieke & Lebofsky 1985), the error ranges of the dereddened magnitude and color are $K_0 = [5.67\text{–}5.83]$ and $(H-K)_0 = [0.03 - 0.24]$. Since the magnitude range defines a band in the HR-diagram and the color range corresponds to a range of temperatures of $[3550\text{–}7000]$ K, these data define the grey shaded band in Fig. 3. The comparison of this band with theoretical PMS tracks suggests that the companion is a very young intermediate- or low-mass ($M \lesssim 6\,M_\odot$) star.

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[1] We assume that the extinction to the companion is the same as to the primary. Although one might expect the companion, being a very young stellar object, to be surrounded by circumstellar material which might cause additional extinction, we believe that the strong radiation and wind of $\Theta^1$Ori C would have dispersed any diffuse material in its immediate vicinity very quickly.

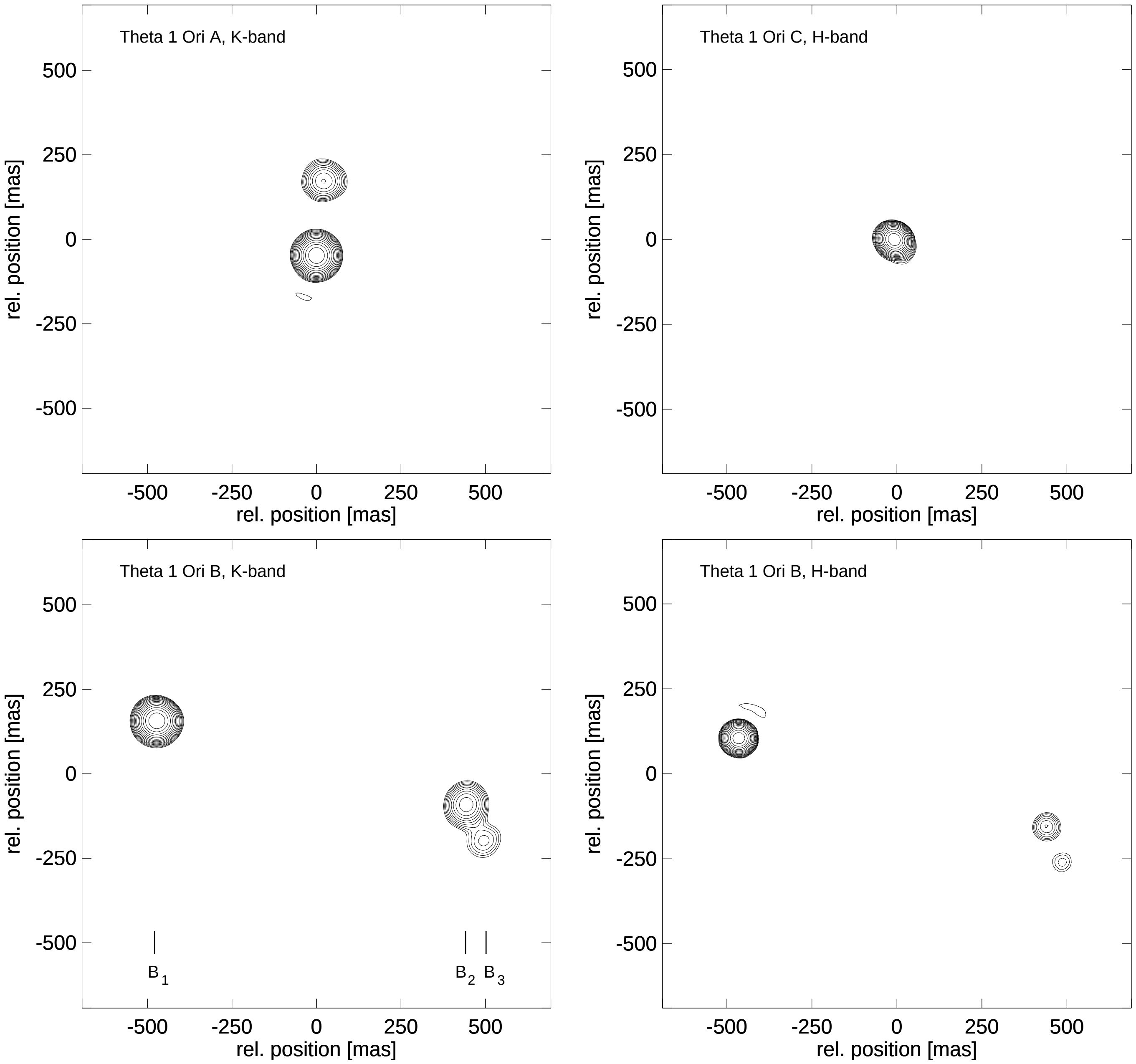

**Fig. 2.** Diffraction-limited images of $\Theta^1$Ori A ($K$-band), B ($H$- and $K$-band), and C ($H$-band) reconstructed by the bispectrum speckle interferometry method. The contour level intervals are 0.25 mag, down to 3.75 mag difference relative to the peak intensity. North is up and east is to the left.

For $\Theta^1$Ori A$_2$ a similar computation (using the $H$-band flux ratio from P98) yields $K_0 = [7.18–7.25]$ and $(H-K)_0 = [-0.01 - 0.09]$. The corresponding band in the HRD suggests a mass of $M \approx 3{-}5\,M_\odot$

The lack of photometric $H$-band data for the components of $\Theta^1$Ori B prevents us from placing them into the HRD. Nevertheless, we can derive upper limits for the masses from the $K$-band flux ratios if we assume that the stars lie at or above, but not below, the main-sequence. The corresponding limits are $M < 5\,M_\odot$ for B$_2$, $M < 3.5\,M_\odot$ for B$_3$, and $M < 2\,M_\odot$ for B$_4$ (the faint companion detected by Simon et al. 1999).

## 4. Multiplicity of the massive Trapezium stars

Several recent studies (P98; Simon et al. 1999) have concordantly found that the binary frequency of the low-mass stars in the Orion nebula cluster (ONC) is comparable to that of solar type field stars, which is about 60% with a median number of companions per primary of about 0.5 (c.f. Duquennoy & Mayor 1991; Fischer & Marcy 1992). The binary frequency of O-type and early B-type field stars seems to be similar (cf. Abt 1983; Mason et al. 1998).

Our detection of $\Theta^1$Ori C$_2$ increases the number of known companions to the four Trapezium stars to 7. The average num-

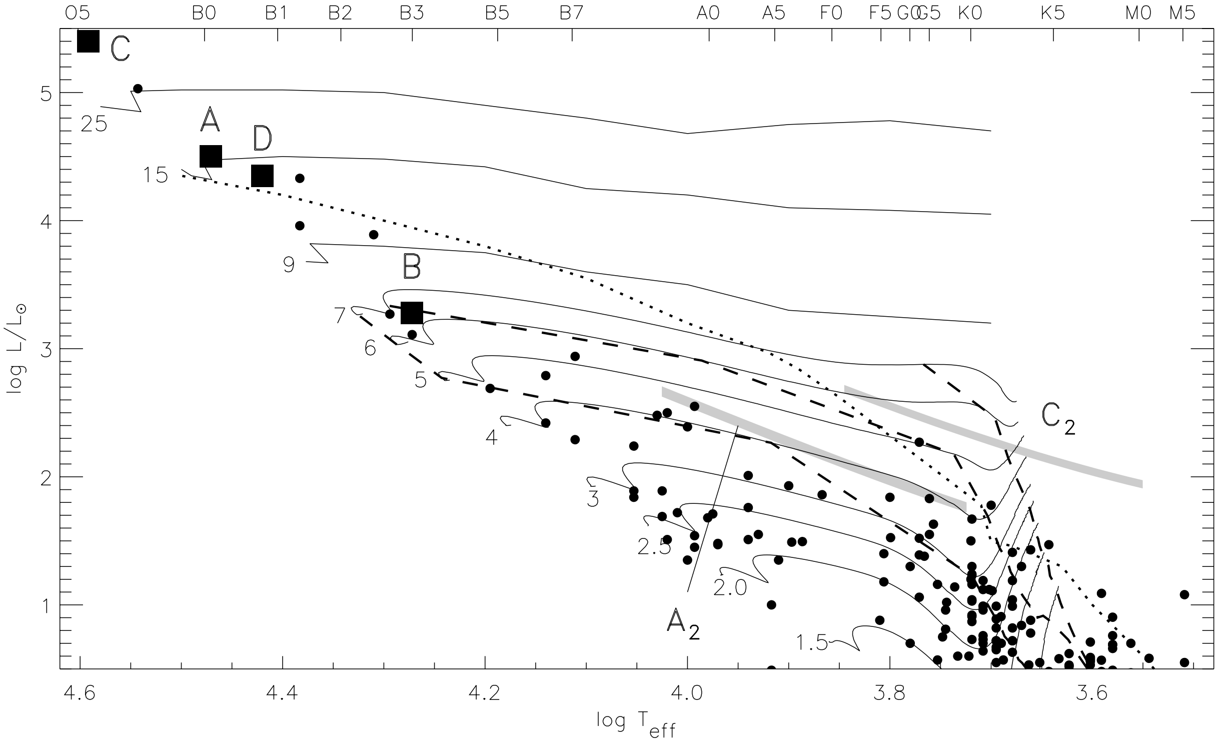

**Fig. 3.** HRD with PMS evolutionary tracks (labelled by the corresponding masses in $M_\odot$) from Siess et al. (1997) for $M \leq 7\,M_\odot$ and from Bernasconi & Maeder (1996) for $M \geq 9\,M_\odot$. The dashed lines show isochrones for ages of 0.1, 0.3, and 1 Myr. The dotted line shows the stellar birthline (c.f. Palla & Stahler 1993) for an accretion rate of $10^{-4}\,M_\odot\,{\rm yr}^{-1}$. The positions of the primary stars are shown by the squares. The grey bands show the locations of the speckle companions $A_2$ and $C_2$, as described in the text. The dots show other YSOs compiled from Hillenbrand (1997), Preibisch (1999), and van den Ancker et al. (1998).

ber of at least 1.75 companions per primary among the high-mass Trapezium stars is clearly higher than the corresponding number for the low-mass stars in the ONC. A similar trend has been found by Abt et al. (1991) and Morrell & Levato (1991): most of the spectroscopic binaries in the ONC are among the O- and early B-type stars, and much less frequent among the later B- and A-type stars. This finding suggests different formation mechanisms for the high-mass and low-mass multiple systems. This is consistent with the recent results of Bonnell et al. (1998) who assumed that high-mass stars form through accretion-induced collisions of protostars. Their theory predicts that close binary systems should be very common among the massive stars. This is supported by our results.

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