Interferometric observations of the multiple stellar system
 δ Velorum
(Research Note)

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ABSTRACT

Context. δ Velorum is a nearby (~24 pc) triple stellar system, containing a close, eclipsing binary (Aa, Ab) discovered in 2000.

Aims. Multiple systems provide an opportunity to determine the set of fundamental parameters (mass, luminosity, size and chemical composition) of coeval stars. These parameters can be obtained with particular precision in the case of eclipsing binaries; for δ Velorum’s components (Aa, Ab) this potential has however not yet been exploited.

Methods. We have analyzed interferometric observations of the close binary (Aa, Ab), obtained with the VINCI instrument and two VLTI siderostats. The measurements, which resolve the two components for the first time, are fitted onto the simple model of two uniformly bright, spherical stars.

Results. The observations suggest that Aa and Ab have larger diameters than expected if they were on the main sequence, and that they are, thus, in a later evolutionary state.

Key words. multiple stars – interferometry – stellar evolutionary state

1. Introduction

δ Velorum (HD 74956) is one of the fifty brightest stars on the sky, with a visual magnitude of $m_V = 1.96$ mag (Johnson et al. 1966). It is a multiple stellar system (e.g. Worley & Douglass 1997), but in spite of its brightness and near distance, $\pi = (40.90 \pm 0.38)$ mas (Perryman et al. 1997), the issue of its composition remains unresolved. As early as 1847, Herschel published his detection of two faint visual companions, δ Vel C and D, at distance 69′′ apart from δ Vel A. Another companion, δ Vel B – at the time separated by ~3′′ from δ Vel A – was later discovered by Innes (1895). The separation 0″736 ± 0″014 between the components A and B appeared surprising when measured by Hipparcos, but it was well explained later, in terms of the orbit computation of Argyle et al. (2002) that showed a highly elliptical orbit of component B with period $P = 142$ yr. In 1979, preliminary results from speckle interferometry suggested an even further component of the system (Tango et al. 1979). This apparent companion was found at a separation of ~0″6 and was taken to be a further component, because for star B the separation at the time was believed to be ~3″. By now, however, it seems very likely that the speckle observations resolved δ Vel B; while there is still an unexplained disagreement for the position angle, the measured small separation does fit well with the orbit of C and D. Finally, the most luminous component, A, was recently recognized to be a close eclipsing binary with a period $T = 45.15$ days (Otero et al. 2000). δ Vel has since been classified as a quintuple stellar system.

This investigation is focussed on the bright eclipsing binary, δ Vel A, but we also argue that δ Vel C and D are not physically associated with δ Vel A, B. While this makes δ Vel a triple system, it takes away little from its challenging potential to obtain important information on stellar evolution. As the inclination, $i$, of its orbital plane is constrained to be close to 90°, an eclipsing binary system provides one of the best means to obtain, in terms of the Kepler laws of motion, fundamental stellar parameters.

In this research note we present the first interferometric observations of the eclipsing binary δ Vel A, obtained with ESO’s Very Large Telescope Interferometer (VLTI) and its “commissioning instrument” VINCI. The measurements resolve, for the first time, this binary system. They are here analyzed with nonlinear least-square fitting methods. We combine our interferometric results with existing photometric and spectroscopic observations, estimate some orbital parameters of the δ Vel A binary system, and discuss, based on the results, the stellar properties of the individual components.

2. Characteristics of δ Vel A derived from previous measurements

2.1. Orbit orientation and eccentricity

In this subsection, a priori estimates of two orbital parameters of the δ Vel (Aa-Ab) system are derived from the time interval
between the eclipses and their durations, the eccentricity, $e$, and the angle, $\omega$, between the semi-major axis and the line of sight. The angle $\omega$ is similar to, but must not be confused with the more generally used parameter longitude of periastron.

As reported by Otero et al. (2000) and Otero (2006), the fractional orbital period from the primary to the secondary eclipse equals $\tau_f = 0.43 \pm 0.05$. The secondary eclipse has been observed by the Galileo satellite in 1989, and its duration and depth have been fairly precisely established to be $0.91 \pm 0.01$ days and $\Delta m_{II} = 0.32 \pm 0.02$ (Otero 2006). The same spacecraft observed the primary eclipse several years later, although its measurements had become less accurate then. The approximate duration and depth of the primary eclipse are $0.51 \pm 0.05$ days and $\Delta m_{II} = 0.51 \pm 0.05$ (Otero 2006). The ratio of durations thus amounts to $\rho_f = 1.78 \pm 0.19$.

The relative motion of the two stars $\delta$ Vel Aa and Ab is taken to be independent of external forces, and the vector, $s$, from Ab to Aa traces an elliptical orbit around Ab as a focal point. As the photometric light curve indicates a total eclipse for $\delta$ Vel A, the inclination of the orbit needs to be close to 90°. To simplify the equations, we assume $i = 90°$. Ab is taken to be the star with the higher surface brightness. During the primary eclipse, which is deeper, Ab is thus eclipsed by Aa. The angle $\theta$ of $s$, also called the true anomaly, is zero at periastron and increases to $\pi$ as the star moves towards apastron. The distance between the stars depends on $\theta$ according to the relation:

$$s(\theta) = a(1 - e^2)/(1 + e \cos(\theta))$$  \hspace{1cm} (1)

where $a$ denotes the semi-major axis. In line with Kepler’s second law the vector $s$ covers equal areas per unit time. The fractional orbital period to reach angle $\theta$ is, accordingly:

$$\tau(\theta) = \frac{2}{A} \int_{0}^{\theta} s^2(\theta')d\theta'$$  \hspace{1cm} (2)

$$= [2\arctan(f_1 \tan(\theta/2)) - f_2 \sin(\theta)/(1 + e \cos(\theta))] / 2\pi$$  \hspace{1cm} (3)

where $A = \pi a^2 \sqrt{1 - e^2}$ equals the area of the ellipse. $f_1 = \sqrt{(1 - e)/(1 + e)}$ and $f_2 = e \sqrt{(1 - e^2)}$.

During the primary eclipse, when the star with the lower surface brightness, Aa, covers Ab, the vector $s$ is directed towards Earth, and $\theta$ equals $\omega$. During the secondary eclipse $\theta$ equals $\omega + \pi$. Thus:

$$\tau_f = 0.43 \pm 0.05$$  \hspace{1cm} (4)

$$= \int_{\omega}^{\omega+\pi} d\theta/(1 + e \cos(\theta))^2$$  \hspace{1cm} (5)

$$= [\arctan(f_1 \tan((\omega + \pi)/2)) - \arctan(f_1 \tan(\omega/2))]$$

$$+ f_2 \sin(\omega)/(1 - e^2 \cos(\omega)^2)] / \pi$$  \hspace{1cm} (6)

which determines $\omega$ for any given eccentricity, $e$ (Fig. 1). The orbital velocity decreases as $\theta$ goes from zero to $\pi$, i.e. from the periastron to the apastron. In the subsequent interval, $\pi$ to $2\pi$ (or $-\pi$ to $0$), it increases again. If the line of sight contained the orbital minor axis, i.e. $\omega = \pi/2$ or $-\pi/2$, the maximum and minimum values of $\tau$ would be reached. Values of $\tau$ less than 0.5 are thus associated with negative $e$ values. Since the fractional orbital period from the primary to the secondary eclipse is 0.43, the angle $\omega$ must lie between $-\pi$ and 0. As Fig. 1 shows, the eccentricity needs to be larger than $\approx 0.03$.

On the other hand, $\omega$ can be further constrained through the ratio of the eclipse durations as follows. The eclipse durations are inversely proportional to the product $r \, d\theta/dr$ of radius and angular velocities during the eclipses. They are thus proportional to $s(\theta)$, and their ratio is:

$$\rho(\omega) = (1 - e \cos(\omega))/(1 + e \cos(\omega))$$  \hspace{1cm} (7)

Given $\rho_f = 1.78 \pm 0.19$, this leads to a second relation between $e$ and $\omega$. As illustrated by Fig. 1, simultaneous agreement with both observed values $\tau_f$ and $\rho_f$ is reached only if $e \in [0.23 - 0.37]$ and $\omega \in [-0.1 - 0.7]$ rad.

2.2. Semi-major axis and stellar parameters

Orbital motion in the triple system $\delta$ Vel(Aa+Ab+B) has recently been substantiated and analyzed by Argyle et al. (2002). From position measurements taken over a period of roughly 100 years the authors inferred a P = 142 yr orbit for component B, and deduced a total dynamical mass $M(Aa) + M(\text{Ab}) + M(B) = 5.7^{+1.27}_{-0.98} M_\odot$. Photometric and spectroscopic measurements of the individual components being few and partly inconclusive, individual mass estimates are still difficult.

$Hipparcos$ measured an apparent magnitude of $H_P = 1.991$ for $\delta$ Vel A and $H_P = 5.570$ for $\delta$ Vel B. With the transformations given by Harmanec (1998), the approximate Johnson V magnitudes are $m_V = 1.99$ and $m_V = 5.5$ for $\delta$ Vel A and $\delta$ Vel B, respectively. But the colours of the individual $\delta$ Vel components being unknown, it needs to be noted that the uncertainty of $m_V$ can be as high as $\approx 0.07$ mag. Since $\delta$ Vel is close ($d = 24.45$ pc according to $Hipparcos$) no interstellar reddening towards the source needs to be assumed, and hence, the absolute magnitudes are $M_V \approx 0.05$ for $\delta$ Vel A and $M_V \approx 3.6$ for $\delta$ Vel B.

Several authors have analyzed spectra of $\delta$ Vel A (e.g. Wright 2003; Alekseeva 1997; Levato 1972; Gray & Garrison 1987). Many of their measurements have probably included $\delta$ Vel B, but its flux is too low to add a significant contribution. From the metal line ratios and Balmer line equivalent widths all authors deduced either spectral type A0 V or A1 V. This being most likely an average classification of the two stars, Aa and Ab, one star should be slightly hotter and the other cooler than a A0/IV star. No signatures of a double-lined spectroscopic binary were reported in any of the spectroscopic observations.
Based on the spectrophotometric information referred to above, and under the assumption that all δ Vel components are on the main sequence, it is suggested that Aa and Ab are of spectral type between A0V and A5V with masses in the range 2.0–3.0 M☉. Furthermore it follows that B is an F-dwarf with mass about 1.5 M☉. This agrees reasonably with the total dynamical mass derived by Argyle et al. (2002).

An a priori estimate of the semi-major axis, a, of the Aa–Ab system is next derived from the mass sum of Aa+Ab (5 ± 1 M☉) and its orbital period (T = 45.150 ± 0.001 days), which leads to a = (6.4 ± 0.5) × 10⁻³ m= 0.43 ± 0.04 AU.

If they are main sequence early A stars, Aa and Ab should have stellar diameters between 1.7–2.4 D☉.

Finally, the depths of the eclipses can be used to constrain the surface brightness ratio φ of the two eclipsing components, δ Vel Aa and Ab,

\[ 1.28 \leq \phi = \frac{1 - 10^{-\Delta m/2.5}}{1 - 10^{-\Delta m/3.5}} \leq 1.67 \] (8)

3. VLT Interferometer/VINCI Observations

3.1. Data description

During April–May 2003, the ESO Very Large Telescope Interferometer (VLTI) was used to observe the eclipsing binary δ Vel(Aa+Ab) in the K-band at four orbital phases with the single-mode fiber based instrument VINCI (Glindemann 2001; Kervella et al. 2003). The observations were performed with two siderostats, placed at stations B3 and M0, separated by 155.368 m. Table I summarizes the resulting data.

Every interferometric observation yields a fringe contrast or squared visibility, V², whose variations are not only due to interferometric modulation, but also to atmospheric and instrumental fluctuations. Accordingly the raw squared visibilities need to be calibrated by a reference star. To this purpose the observations of δ Vel were combined with observations of HD 63744, a star of spectral type K0III, with an estimated diameter of 1.63 ± 0.03 mas (Bordé et al. 2002). The interferometric measurements were then analyzed by use of the VINCI data reduction pipeline, described in detail in Kervella et al. (2003).

Additionally, the calibrated V² values need to be corrected for the influence of the nearby component δ Vel B. The diffraction on the sky (through an individual VLTI 0.4 m siderostat) of the fiber fundamental mode, which defines the interferometric field of view, is equivalent to an Airy disk with a 1″.38 diameter.

At the time of the observations Aa+Ab and B were separated by ~ (1.0 ± 0.3)″. Depending on atmospheric conditions, the interferograms are, therefore, contaminated by a random and time varying fraction of light, i.e. an incoherent signal, from star B. The visibilities must, accordingly, be multiplied by a factor:

\[ V_c = V \times (1 + I_B/I_{Aa+Ab}) = (1.05 \pm 0.05) \times V \] (9)

I_B and I_{Aa+Ab} are the intensities collected by the interferometer from δ Vel B and δ Vel(Aa+Ab). I_B/I_{Aa+Ab} lies between 0 (no light from B) and 10⁻² ≃ 0.09 (star B is completely in the field of view), where Δm ∼ 2.6 equals the K-band magnitude difference between B and Aa+Ab.

3.2. Comparison to a model

The 17 visibility measurements, V², were fitted to a model of a binary system of two uniformly bright spherical stellar discs, observed at K-band with a filter of finite bandwidth. Five parameters of the binary model (stellar diameters D_a, D_b, position angle of the Ascending Node Ω, semi-major axis a, eccentricity e) were adjusted for optimum fit to the observations. The fitting procedure utilizes a non-linear least-squares algorithm (Markwardt 2005) that follows the direction of steepest descent of \( \chi^2 \) in the parameter space, \( \chi^2 \) being the reduced sum of squared deviations, i.e. the sum divided by the 13 degrees of freedom. To distinguish between local and absolute minima, the initial parameters were varied over the broad ranges of their potential values:

The semi major axis, a, was considered between 5.4 × 10¹⁰ m and 8.0 × 10¹⁰ m, which corresponds to a total mass of Aa and Ab in the range 3–10 M☉. As specified in Sec. 2 e ∈ [0.23, 0.37]. The stellar diameters were examined between 0.4 and 12.4 mas. These limits refer respectively to the resolution limit of the interferometer and to the Roche lobe volume diameter D_L. The latter is approximated to better than 1% by D_L/d ∼ 12.4 mas (Eggleton 1983). If one of the stars were to have a diameter larger than D_L, the system would be an interacting binary and the simple model of two spherical, uniformly bright stars would

| Date       | Julian Date - 2452700 | Phase | V² ± σV², % | N/value |
|------------|-----------------------|-------|--------------|---------|
| 21 Apr 03  | 50.628                | 0.937 | 57.40±3.60% | 383     |
| 50.633     | 0.937                 | 54.20±3.60% | 298     |
| 50.639     | 0.937                 | 54.00±3.50% | 311     |
| 03 May 03  | 62.498                | 0.200 | 27.54±0.66% | 96      |
| 62.502     | 0.200                 | 34.03±0.70% | 393     |
| 62.507     | 0.201                 | 43.40±2.20% | 260     |
| 62.512     | 0.201                 | 42.20±5.07% | 68      |
| 62.542     | 0.201                 | 13.37±0.45% | 80      |
| 62.545     | 0.201                 | 8.47±0.58%  | 122     |
| 62.554     | 0.202                 | 5.06±0.17%  | 356     |
| 62.562     | 0.202                 | 15.32±0.33% | 416     |
| 10 May 03  | 69.531                | 0.337 | 44.30±1.80% | 435     |
| 69.536     | 0.357                 | 52.20±2.00% | 446     |
| 69.551     | 0.357                 | 56.40±2.10% | 455     |
| 11 May 03  | 70.492                | 0.377 | 8.30±0.45%  | 258     |
| 70.506     | 0.378                 | 2.92±0.40%  | 116     |
| 70.519     | 0.378                 | 1.30±1.40%  | 45      |

Fig. 3. \( \chi^2 \) as a function of the stellar diameters. The three other parameters of the model are set equal to: a = (5.7 ± 0.3)×10¹⁰ m, e = 0.230 ± 0.05, Ω = 27.4 ± 1.2°.
4. Results and discussion

4.1. The close eclipsing binary δ Vel (Aa-Ab)

The computations could be slightly biased if the diameter of the calibrator star were substantially misestimated, or if HD 63744 were a still undiscovered binary system. On the other hand, HD 63744 is part of the catalog of interferometric calibrator stars by Bordé et al. [2002] with its diameter (1.63 ± 0.03 mas) specified to a precision of 1.8%. Furthermore, it has been studied simultaneously with other calibrator stars in VINCI observations by one of the authors (P. Kervella). In these investigations the visibilities of HD 63744 equaled those expected for a single star of 1.63 ± 0.03 mas diameter. Thus, HD 63744 appears to be a reliable calibrator.

A perhaps more relevant aspect are possible astrophysical complexities of δ Vel (Aa+Ab) that are disregarded in the model of two uniformly bright, spherical stars. In particular, the rotational velocities of Aa and/or Ab are found to be high, with values of −150 - 180 km/s (Royer et al. [2002] Hempel et al. [1998] Holwege et al. [1999]), which indicates that the two stars need not be uniformly luminous nor circular.

Another possible over-simplification of our binary model is the constraint on the orbital inclination, i, being fixed at 90°. Given the fitted semi-major axis and stellar diameters, we note that the eclipse durations (0.51 ± 0.05 days and 0.91 ± 0.01 days) are shorter than they should be in the case of i = 90°, where the duration of the longer eclipse would have to exceed D_b T/(2π a) = 1.06 days. We conclude that i is ∼ 88° or ∼ 92°, rather than 90°. All observations were performed out of eclipse and, therefore, the visibility values are nearly unaffected by such a small variation in i. With substantially more visibility measurements and an increased number of fitted parameters, the issue on the precise orbital inclination might be addressed in more detail.

The most important and remarkable result of our analysis is that the stellar diameters of Aa and Ab are found to equal 6.0 ± 0.5 D⊙ and 3.3 ± 0.6 D⊙, respectively. This exceeds significantly, by factors ∼ 1.4 - 3, the values expected if Aa and Ab are main sequence stars. If both diameters are constrained to lie below 2.5D⊙, the best fit corresponds to χ² = 16.7, which is far beyond
the present result and confirms that large diameters are required to account for the measured visibilities.

4.2. On the physical association of δ Vel C and D

Ever since the observations of Herschel (1847), δ Vel has been taken to be a visual multiple star, δ Vel C and D being the outer components of the system. With $m_V$ of 11.0 mag and 13.5 mag respectively (Jeffers et al. [1963]), C and D would need to be of late spectral type, certainly no earlier than M, if they were at similar distance as δ Vel (Aa+Ab+B). To our knowledge, the only existing spectra of C and D were recorded during a survey of nearby M dwarfs (Hawley et al. [1996]). While the limited range and resolution of the spectra precluded ready determination of the spectral types of C and D, they were nevertheless estimated as $\sim$G8V and $\sim$K0V. Therefore, given their apparent magnitudes, C and D must be at much further distances than δ Vel (Aa+Ab+B). We conclude, that δ Vel C and D are not physically associated. Hence, δ Vel ought to be classified as a triple stellar system only.

5. Summary

Seventeen VINCI visibility measurements of δ Vel (Aa+Ab) were fitted onto the model of two uniformly bright, spherical stars. The adjustment to the measurements does not provide individual diameters compatible with A-type main sequence stars. The two stars appear, thus, to be in a more advanced evolutionary stage. More data are, however, needed to ensure this result. As the stellar evolution is fast during this period, more detailed knowledge of the system might also constrain the models more tightly. Precise photometric and spectroscopic observations of the eclipses should provide the separate intensities and chemical compositions of Aa and Ab and, hence, permit further inferences on the age and evolutionary state of δ Vel.

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