A THIRD MASSIVE STAR COMPONENT IN THE \sigma ORIONIS AB SYSTEM

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ABSTRACT

We report on the detection of a third massive star component in the \sigma Orionis AB system, traditionally considered as a binary system. The system has been monitored by the IACOB Spectroscopic Survey of Northern Massive Stars program, obtaining 23 high-resolution FIES@NOT spectra with a time span of \(\sim 2.5\) years. The analysis of the radial velocity curves of the two spectroscopic components observed in the spectra has allowed us to obtain the orbital parameters of the system, resulting in a high eccentric orbit \((e \sim 0.78)\) with an orbital period of \(143.5 \pm 0.5\) days. This result implies the actual presence of three stars in the \sigma Orionis AB system when combined with previous results obtained from the study of the astrometric orbit (with an estimated period of \(\sim 157\) years).

Key words: binaries: spectroscopic – galaxies: star clusters: individual (\sigma Orionis) – stars: early-type – stars: individual (\sigma Ori AB)

Online-only material: color figures

1. INTRODUCTION

The \sigma Ori star \((V \sim 3.80\) mag, HD 37468, HR 1931) is visible to the naked eye at about 1 deg to the south of Alnitak (\(\zeta\) Ori), the easternmost bright star of the Orion Belt, and at a comparable separation to the west of the Horsehead Nebula. The actual multiple status of \sigma Ori was first described in Tabula Nova Stellarum Duplicium, where Mayer (1779) tabulated the stars known today as \sigma Ori A and \sigma Ori E, separated by 42 arcsec, and proposed a third component between them. Struve et al. (1876), from observations between 1819 and 1831, confirmed the third component, \sigma Ori D, and reported a new “ash”-colored one, \sigma Ori C. The brightest star in the system was found to be, in its turn, a tight binary by Burnham (1892). The two components, historically known as \sigma Ori A and \sigma Ori B, are thought to have very early spectral types (O9.5 V and B0.5 V, respectively) and are separated by no more than 0.3 arcsec.

The angular separations \(\rho\) and \(\theta\) between \sigma Ori A and B have been frequently monitored during the last 120 years by numerous authors with micrometers, first, and speckle imaging and adaptive optics, next. Some orbit determinations have been published by Kümritz (1958), Heintz (1974, 1997), Hartkopf et al. (1996), and Turner et al. (2008). The relatively long orbital period \((P \sim 157\) years, i.e., the binary has not completed a whole revolution since its discovery), wide projected physical separation \((s \sim 100\) AU, assuming \(d \sim 350–450\) pc), and early spectral types have suggested that \sigma Ori A and B may form “the most massive visual binary known”, with up to \(40\) \(M_\odot\) (Heintz 1974; Caballero 2008a).

The small orbital semimajor axis of only \(0.266 \pm 0.002\) arcsec and nearly circular orbit (Turner et al. 2008) makes an individualized spectroscopic study impractical. Predicted radial-velocity variations in the primary have a considerable peak-to-peak amplitude of about \(7\) km s\(^{-1}\) (Hartkopf et al. 1996), but the long orbital period, magnitude difference between both components \((\Delta H_P = 1.21 \pm 0.05\) mag; Perryman et al. 1997), and scarcity of adequate high-resolution spectra in the last century complicate any long-term spectroscopic study. Some authors have reported, however, that at certain epochs the spectrum of \sigma Ori “A–B” changes in appearance from its single-line stage, showing broadened and double lines separated by up to \(280\) km s\(^{-1}\) (Frost & Adams 1904; Frost et al. 1926; Miczaika 1950; Bolton 1974; Fullerton 1990; Morrell & Levato 1991; D. M. Peterson 2009, private communication). The timescale of these variations was only a few months. Both observational results would not be expected from the study of the astrometric orbit and could suggest that the \sigma Ori “A–B” system is a triple system (one of the stars resolved visually being a double-lined spectroscopic binary, viz. Bolton 1974). Nevertheless, the vast majority of the spectrophotometric observations of \sigma Ori “A–B” have not been able to resolve the spectroscopic binary and, in the words of Frost & Adams (1904), “evidences of complexity in the spectrum [of \sigma Ori are] scarcely sufficient to justify conclusions on the subject.” More than a century later the “subject” is not resolved yet.

The Trapezium-like \sigma Ori system being, a double or a triple massive star, has major implications because of its location in the center of the homonymous \sigma Orionis cluster, which is a cornerstone for star formation studies (Garrison 1967; Wolk 1996; Béjar et al. 1999; Walter et al. 2008; Caballero 2008b). First, the top of the (initial) mass function and the long-term dynamical evolution of the cluster depend on the actual mass of the brightest stars (Sherry et al. 2004; Caballero 2007). Second, any derivation of theoretical masses of intermediate- and low-mass stars and substellar objects rely on a precise value of the cluster heliocentric distance, which is often determined from fits of the cluster sequence in color–magnitude diagrams (e.g., Sherry et al. 2008; Haywood & Naylor 2008) or via dynamical parallaxes (Caballero 2008a); both procedures must take into account the multiplicity of \sigma Ori “A–B.” Finally, the “photoerosion of pre-existing cores” (Whitworth et al. 2007, and references therein) by the strong high-energy radiation emitted by the Trapezium-like system may partially explain the copiousness of cluster brown dwarfs and planetary mass objects.
2. OBSERVATIONS, ANALYSIS, AND RESULTS

The \(\sigma\) Ori “A–B” system is one of the massive binary/multiple systems monitored by the IACOB spectroscopic survey of Northern Galactic OB stars project (Simón-Díaz et al. 2011). Using the cross-dispersed Fibre-fed Échelle Spectrograph (FIES) at the Nordic Optical Telescope, we have gathered so far 23 high-resolution \((R = 46,000)\) spectra with a time span of \(\sim 2.5\) years (between 2008 November and 2011 April; see Table 1). Our observations have been complemented with one spectrum each of \(\sigma\) Ori D (B2 V) and \(\sigma\) Ori E (B2 Vpe), the other two massive star components in the \(\sigma\) Ori system. We refer to Simón-Díaz et al. (2011) for a description of the spectroscopic observations and the IACOB database.

Representative examples of the obtained spectra are shown in Figure 1, along with the spectra of \(\sigma\) Ori D and E for comparison. At first glance, the spectra of \(\sigma\) Ori “A–B” show two spectroscopic components, a narrow one and a broad one, varying on a timescale of weeks. The shown spectra have been corrected for heliocentric velocity and shifted to the systemic velocity of the cluster \((+30.93 \pm 0.92 \text{ km s}^{-1})\), as determined by Sacco et al. (2008) from dozens of FLAMES spectra of single low-mass stars in the \(\sigma\) Orionis cluster. While the spectra of \(\sigma\) Ori D and E show single, broad components at the cluster systemic velocity, those of the two spectroscopic components of \(\sigma\) Ori “A–B” move around that value.

The \(\text{He}\ i \lambda 5875\) line was used to determine the radial velocity of both spectroscopic components of \(\sigma\) Ori “A–B” for the 23 compiled spectra. This strong line makes disentangling of both components easier and provides more reliable radial velocity measurements than other metal lines, for which the broad component appears too faint. Besides, the helium line is close to the interstellar Na \(\text{i} \lambda 5890, 5895\) doublet, which can be used as a sanity check of velocity shifts and heliocentric velocity correction.

The radial velocities were determined by means of a two-parameter cross correlation of the observed spectra with a grid of synthetic spectra built with two rotationally broadened, radial velocity-shifted \((v_{\text{rad,1}} \text{ and } v_{\text{rad,2}})\) \(\text{He}\ i \lambda 5875\) line profiles computed with the FASTWIND stellar atmosphere code (Puls et al. 2005). Previously, the projected rotational velocities had been determined by applying the Fourier method (Gray 1976; see also Simón-Díaz & Herrero 2007 for a recent application to OB stars) to the spectrum observed on 2010 September 9, when both components were not blended. We derived \(v \sin i\) values of \(30 \pm 3\) and \(130 \pm 10\) km s\(^{-1}\) for the narrow and broad components, respectively.

The resulting radial velocities, together with the associated uncertainties, are listed in Table 1. The “Aa” and “Ab” components correspond to the broad- and narrow-line spectra, respectively.

First, we used CLEAN (Roberts et al. 1987), under an adapted version of the original code particularly useful for unequally spaced data, for deriving a preliminary orbital period of

![Figure 1](image_url)
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Figure 2. Upper panel: radial velocity curves of σ Ori Aa (triangles) and Ab (squares) phased to the period \( P = 143.5 \) days. Error bar sizes are smaller than those of symbol sizes. Vertical dotted line indicates the systemic velocity (see Table 2). Lower panels: velocity residuals to the adopted fit for the two components.

(A color version of this figure is available in the online journal.)

147 ± 6 days. Next, we applied the Lehmann–Filhés method implemented in sbop (Etzel 2004) for a detailed orbital analysis. We computed the orbital solutions for periods between \( P_{SB2} = 141.0 \) and 147.0 days in steps of 0.5 days and found that the \( \chi^2 \) of the radial velocity curves of both broad and narrow components minimized at \( P_{SB2} = 143.5 \) days. We thus assumed an error of 0.5 days in the orbital period of the double-line spectroscopic binary (SB2). The final orbital solution is shown in Table 2 and illustrated in Figure 2.

The derived spectroscopic orbital period, of about 0.39 years, is roughly 400 times smaller than the astrometric orbital period of \( \sim 157 \) years. Then, we face a hierarchical triple system containing a close SB2 (the components Aa and Ab) with a period of a few months and a fainter astrometric companion (the component B) orbiting a common center of gravity with a period of over a century. This scenario is also compatible with the good agreement found between the center-of-mass velocity obtained for σ Ori Aa and Ab and the systemic velocity determined for the cluster by Sacco et al. (2008). Following predictions by Hartkopf et al. (1996) both quantities should not differ by more than \( \sim 4 \) km s\(^{-1}\).

3. DISCUSSION

A small region of the spectrum of σ Ori Aa+Ab+B obtained on 2010 September 9 (corresponding to the largest separation between the broad and narrow components) is displayed in Figure 3. The selected region contains the \( \text{He} \ ii \ \lambda 4541 \) line and the \( \text{Si} \ iii \ \lambda \lambda 4552, 4567, 4574 \) triplet, traditionally considered to establish the spectral type of late O- and early B-type dwarfs. The spectra of the standard stars HD 34078 (AE Aur) and HD 36960 from the IACOB spectroscopic database (Simón-Díaz et al. 2011) are also shown in the figure. The two spectra were convolved to the projected rotational velocities of the broad and narrow components of σ Ori Aa and Ab (Section 2), shifted to the radial velocities indicated in Table 1, and diluted by factors 0.500 and 0.275, respectively.

Three conclusions can be made from Figure 3: (1) the two spectroscopic components are nicely fitted by the spectra of the O9.5 V and B0.5 V standards, (2) in a lower resolution spectrum (or even at a phase in which both components are closer) the spectrum of σ Ori Aa+Ab+B could be erroneously classified as a “single” O9.7 V star (e.g., Sota et al. 2011), and (3) there is no clear evidence of the B component, which should be located close to the systemic velocity of the σ Ori cluster, making its

Figure 3. Spectral region showing the \( \text{He} \ ii \ \lambda 4541 \) and \( \text{Si} \ iii \ \lambda \lambda 4552, 4567, 4574 \) lines of σ Ori Aa+Ab+B at the epoch of the widest separation between components (black solid), HD 34078 (O9.5 V; red dashed) and HD 36960 (B0.5 V; blue dash-dotted). The position of the lines for the components σ Ori Aa [left], Ab [right], and B [center] (measured in the case of the former ones, and expected in the case of the latter one) are indicated in the lower part.

(A color version of this figure is available in the online journal.)

Table 2
Orbital Parameters of σ Ori Aa and Ab

| Parameter | Value | Units |
|-----------|-------|-------|
| \( P_{SB2} \) | 143.5 ± 0.5 | days |
| \( T \) | 2455452.03 ± 0.18 | days |
| \( e \) | 0.7834 ± 0.012 | |
| \( \gamma \) | +29.8 ± 0.3 | km s\(^{-1}\) |
| \( M_{Aa}/M_{Ab} \) | 1.23 ± 0.07 | |

\( K \) | 75 ± 4 | km s\(^{-1}\) |
\( \omega \) | 208 ± 0.9 | deg |
\( a \sin i \) | 154 ± 7 | \( R_\odot \) |
\( M \sin^3 i \) | 9.3 ± 0.8 | \( M_\odot \) |

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spectral classification difficult. From the observed magnitude differences with respect to Aa+Ab (see, e.g., ten Brummelaar et al. 2000; Caballero 2008a; Maíz Apellániz 2010), the third star must be an early-B dwarf, slightly cooler and less massive.

In spite of the complexity of the system, we can estimate approximate individual masses of the hierarchical triple system by applying the third Kepler law (i.e., \( M_{Aa} + M_{Ab} + M_{B} \) \( P^2 = a^3 \)), where \( a = d \) is the physical semimajor axis in AU, \( d \) is the heliocentric distance in pc, \( P \) is the astrometric orbital period in years, and \( M_i \) are the stellar masses in \( M_\odot \). The system total increases to over 60 \( M_\odot \) if we also take into account \( \sigma \) Ori C, D, and E.

The existence of an additional powerful ultraviolet source and of a deeper central gravity well than previously thought has a critical impact on the way the astronomers see the \( \sigma \) Orionis cluster and its surroundings. In addition, the dynamical properties of the central, young triple system deserve further observational and theoretical studies in the framework of the evolution of highly eccentric massive binaries and massive star formation theories.

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