AN UPPER LIMIT TO THE MASS OF A CLOSE COMPANION CANDIDATE TO σ ORI E

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The famous, very young, helium rich, magnetically-active, radio and X-ray emitter, short-period rotationally variable, spectroscopically peculiar star σ Ori E may have a close late-type stellar companion, which could explain flaring activity observed in some σ Ori E X-ray light curves. In 2009, Bouy et al. announced the detection of a faint companion candidate in the Ks band at 0.330 arcsec (130 AU) to the B2 Vp primary. Here, we carry out z'-band lucky imaging with AstraLux at the 2.2 m Calar Alto telescope in an attempt to constrain the properties of the companion candidate to σ Ori E. We impose a maximum mass of 2.0±0.2 M\textsubscript{sol} and an earliest spectral type of K2±1, which leaves the door open to a new, inexpensive, near-infrared, adaptive-optics study.

Introduction

The helium-rich peculiarity of the spectrum of the B2 Vp star σ Ori E (48 Ori E, V1030 Ori, HD 37479, Mayrit 42062) was first noticed in 1956 by Berger\textsuperscript{1}, and two years later made widely public by Greenstein & Wallerstein\textsuperscript{2}. Six decades later, dedicated works on σ Ori E have received over 1000 citations from approximately 50 dedicated works (e.g., The magnetic field of σ Ori E\textsuperscript{3}, The rigidly rotating magnetosphere of σ Ori E\textsuperscript{4}, Shell and photosphere of σ Ori E – New observations and improved model\textsuperscript{5}, A new phenomenon in the spectrum of σ Ori E\textsuperscript{6}, etc.). Actually, for decades the star attracted more attention than the rest of stars in the 3 Myr-old σ Orionis cluster, which is now a cornerstone for studies of circumstellar discs, coronal emission, accretion, and, especially, the mass function down to the substellar limit and beyond\textsuperscript{7-9}. With an early B spectral type and a mass of 7-8 M\textsubscript{sol}, σ Ori E is one of the most massive stars in the homonymous Trapezium-like system σ Ori, which also gives the name to the cluster and illuminates the Horsehead Nebula\textsuperscript{10-12}.

The B2 Vp star σ Ori E is abnormally rich in helium\textsuperscript{13-17} and magnetically active\textsuperscript{18,19}, it is indeed the prototype of magnetic peculiar Bp stars. Furthermore, it also displays periodic variability of 1.19 d in optical photometry and spectroscopy\textsuperscript{17,20-25}, photospheric and wind absorption lines\textsuperscript{5,26,27}, linear and circular polarization\textsuperscript{18,28-30}, and emission in He\textsubscript{i}\textsuperscript{31,32}, non-thermal radio\textsuperscript{33-37}, and X-rays\textsuperscript{38-41}. According to the most accepted scenarios proposed by Nakajima\textsuperscript{42}, Groote & Hunger\textsuperscript{43}, and Townsend et al.\textsuperscript{44}, the origin of the variability resides on abundance heterogeneities on the stellar surface that rotate rigidly with, and are connected through, radiatively driven wind streams to at least two clouds of
confined plasma in a circumstellar magnetosphere. The very different inclinations of both stellar magnetic and rotational axes shape such a weird configuration.

Besides that, strong X-ray flares in σ Ori E were reported by Groote & Schmitt with ROSAT\textsuperscript{44} and Sanz-Forcada \textit{et al.} with XMM-Newton\textsuperscript{45}. Observed flares are typical in young late-type stars, but virtually missing in early-type stars like σ Ori E. Magnetohydrodynamic simulations supported a centrifugal breakout hypothesis that could explain the reconnection heating and following X-ray flaring from the B2 Vp star\textsuperscript{46,47}. However, centrifugal breakout was afterwards ruled out with an accurate photometric monitoring of σ Ori E with the MOST microsatellite\textsuperscript{25}. Another alternative for explaining the X-ray flares, proposed by Caballero \textit{et al.}\textsuperscript{41,48}, is the existence of an unresolved K-M-type stellar companion. In this scenario, σ Ori E would become a Lindroos binary system made of a B-type primary and a late-type companion\textsuperscript{49,51}.

In 2009, using multi-conjugate adaptive optics in the near infrared, Bouy \textit{et al.}\textsuperscript{52} discovered a companion candidate to σ Ori E, 3–4 mag fainter in Ks, at only ρ ~ 0.330 arcsec and θ ~ 301 deg (note the corrected position angle\textsuperscript{12}). In spite of the numerous works devoted to σ Ori E, this companion candidate at the limit of resolution and sensitivity of the Bouy \textit{et al.} observations has never been confirmed. At the cluster distance of 385 pc\textsuperscript{11,53}, the measured angular separation translates into a projected physical separation of 130 AU. The radius of σ Ori E is of the order of 3–4 R\textsubscript{sol}\textsuperscript{25,30}, while the circumstellar magnetosphere with its two plasma-confinement regions could extend to up to 2.4 stellar radii\textsuperscript{30} (i.e., about 0.04 AU). In spite of the apparently large physical separation between the companion candidate to σ Ori E and its circumstellar magnetosphere, the existence of wind collision and/or magnetic channeling might explain the high order variations to the rigidly rotating magnetosphere model\textsuperscript{4,19}. If it were not the case, a (young, active) late-type companion may at least explain the observed X-ray flares observed by Groote & Schmitt and Sanz-Forcada \textit{et al.}

In this work, we present new, red-optical, lucky-imaging observations of very high spatial resolution with the aim of characterizing the faint companion to σ Ori E and of improving the uncertain measures of position and flux by Bouy \textit{et al.}

\textit{Observations and analysis}

On 22 Oct 2014, we observed σ Ori E (V = 6.61 mag) with the lucky-imaging camera AstraLux Norte\textsuperscript{54} in service mode under director’s discretionary time. AstraLux was attached to the Cassegrain focus of the 2.2 m telescope of the Calar Alto Observatory, in Almería, Spain. We got 50 000 frames of 15 ms in frame-transfer mode for each of the two used passbands, SDSS i’ and z’. We fixed the gain for both filters, did windowing in a 256 × 256-pixel sub-array, used the right part of the electron-multiplying high-speed CCD for excluding the bad column #242, chose the quadrant less affected by dust, and set all other parameters to default. Total exposure time per filter was 750 s. For a precise astrometric calibration, we also observed a field centred on the M3 globular cluster.
We did a standard reduction of the data with the dedicated AstraLux pipeline\textsuperscript{54}, by selecting only the best 1.0, 2.5, and 5.0% of all frames, and by shifting, stacking, and re-sampling them into a nearly diffraction-limited image\textsuperscript{55,56} (the AstraLux pipeline also provides the option of selecting the best 10% frames). The final plate scale was 0.02327 arcsec/pixel. Unfortunately, the $i'$-band image showed an apparent elongation in the north-south direction, probably due to incorrect focussing, and could not be used for the following analysis. The full final $z'$-band image, together with a SofI/NTT image with a larger field of view for comparison, is shown in Fig. 1.

Fig. 2 shows the largest detectable difference of magnitude between primary and secondary in our stacked AstraLux $z'$-band image as a function of angular separation to $\sigma$ Ori E. It was computed from the average of the $3\sigma$ noise measurements in increasing concentric annuli of 1-pixel width centred on our target (the north-south read-out “spikes” barely affects the standard-deviation calculation). The derived maximum magnitude limit is valid for angular separations between 0.25 and 4.6 arcsec. The hunchbacked point-spread function, which avoids quantifying any standard full-width-half-maximum, is typical of all AstraLux images. At the largest separations to $\sigma$ Ori E, the minimum magnitude difference of our stacked image is as high as $\Delta z' = 8.0$ mag, which translates into an apparent magnitude depth of $z' = 15.0$ mag (see below). This companion detectability method is widely used in the literature; see an example by the authors and with this instrument, including hunchbacked point-spread function, generation of artificial signals, and identification of false positives, in Lillo-Box \textit{et al.}\textsuperscript{56}.

Results and discussion

The close companion candidate to $\sigma$ Ori E is at 0.33 arcsec according to Bouy \textit{et al.} At such angular separation, and with an uncertainty of 10%, we imposed a minimum magnitude difference $\Delta z' = 2.9 \pm 0.3$ mag for the 2.5% best AstraLux Norte frames. The magnitude difference for the 1 and 5% best frames is identical within error bars.

We made a simple interpolation between well-calibrated magnitudes of $\sigma$ Ori E in neighbouring passbands\textsuperscript{57,58} for estimating its apparent magnitude in the $z'$-band at 7.04$\pm$0.04 mag ($\sigma$ Ori E saturates in Sloan Digital Sky Survey DR9\textsuperscript{59} $z'$ band). With the AstraLux value of $\Delta z' > 2.9 \pm 0.3$ mag, we concluded that the companion candidate must be fainter than $z' = 10.0 \pm 0.3$ mag. At the $\sigma$ Orionis distance\textsuperscript{53} (distance modulus = 7.93$^{+0.08}_{-0.15}$ mag), this limit translates into a minimum absolute magnitude $M_z = 2.1 \pm 0.3$ mag (see Table I). This magnitude is brighter than that of the most massive, hottest stars in the Lyon BT-Settl models\textsuperscript{60} for 3 Myr (1.4 $M_{\text{sol}}$, 4700 K). Thus, we used the Siess \textit{et al.}\textsuperscript{51} models for 3 Myr, solar metallicity $Z = 0.02$ and no overshooting for putting limits on the astrophysical parameters of the companion candidate.

After making another simple interpolation (the Siess \textit{et al.} models do not tabulate absolute magnitudes in $z'$, but in $R$, $I$, $J$ and $H$, just to mention the neighbouring
passbands), the companion candidate must be less massive than \(2.0^{+0.2}_{-0.1} \, M_{\odot}\), cooler than \(T_{\text{eff}} = 4960^{+190}_{-70} \, K\), and later than K2±1. At 3 Myr, while the B2 Vp primary is already in the main sequence, the companion is still in the contracting phase and has lower surface gravity (and greater mass) than field K dwarfs of the same effective temperature.

The depth of our stacked image allowed also us to discard the existence of lower-mass companions at larger separations. In our AstraLux image, we were not able to identify another source apart from \(\sigma\) Ori E in their deeper MAD near-infrared images, Bouy et al. did not find any other source at less than 5 arcsec to \(\sigma\) Ori E either. In Table II, we show the upper limits of masses and spectral types at four angular separations. We used the Siess et al. models at 1.0 arcsec (as at 0.33 arcsec), and the BT-Settl models for 3 Myr and the \(T_{\text{eff}}\)-spectral type conversion of Reid & Hawley\(^2\) for 2.0 and 3.0 arcsec.

The earliest spectral type of the companion candidate to \(\sigma\) Ori E derived from our AstraLux observations, K2±1, agrees with the “late-K to early-M” spectral-type interval hypothesised by Caballero et al.\(^{18}\) from the existence of X-ray flares. The minimum magnitude difference in \(z^\prime\) between primary and candidate companion is also consistent with the 3–4 mag difference in \(K_s\) estimated by Bouy et al. The ESA Gaia mission will unlikely be able to resolve any very close companion 7–8 mag fainter in \(G\) than the bright primary\(^{63}\). Besides, given the very low cluster proper motion (\(\mu < 5 \, \text{mas/yr}\)) and its location in the antapex\(^{64}\), an astrometric follow-up of the pair may not be feasible, even with Gaia. Therefore, new high-resolution multi-band imaging in the red optical and/or near-infrared, deeper by about 2 mag than our current AstraLux data, are necessary to constrain the properties of the companion candidate at 0.33 arcsec to \(\sigma\) Ori E. The Hubble Space Telescope could easily answer this dilemma (the primary star may be too bright for the James Webb Space Telescope), but a near-infrared adaptive-optics system at a 4–8 m ground telescope, such as NACO, SPHERE, GPI or MagAO, could do it faster and cheaper in just 10 min of observing time (around 30 min including overheads). The over 1000 citations and six decades of time-consuming works on \(\sigma\) Ori E may deserve this small observational effort.
Table I
Apparent and absolute magnitudes in the red optical and near-infrared of σ Ori E and its close companion candidate

| Band | σ Ori E | Companion candidate |
|------|---------|---------------------|
|      | Apparent magnitude [mag] | Absolute magnitude [mag] | Apparent magnitude [mag] | Absolute magnitude [mag] |
| R    | 6.84±0.01 | -1.09±0.08-0.15     | ... | ... |
| I    | 7.08±0.01 | -0.85±0.08-0.15     | ... | ... |
| z'   | 7.04±0.04 | -0.89±0.10-0.16     | >10.0±0.3 | >2.1±0.3 |
| J    | 6.97±0.026 | -0.96±0.08-0.15    | ... | ... |
| H    | 6.95±0.031 | -0.98±0.09-0.15    | ... | ... |

Table II
Upper limits to the presence of resolved companions to σ Ori E

| ρ [arcsec] | s [AU] | z' [mag] | $M_{max}$ [M$_{sol}$] | Earliest sp. type |
|------------|--------|----------|-----------------------|------------------|
| 0.33       | 130    | 10.0±0.3 | 2.0±0.2-0.1           | K2±1             |
| 1.00       | 385    | 10.9±0.3 | 0.65±0.15             | K4±1             |
| 2.00       | 770    | 12.6±0.3 | 0.69±0.09             | K7±1             |
| 3.00       | 1160   | 14.3±0.3 | 0.25±0.04             | M3±1             |

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FIG. 1

Left: part of a SofI/3.6 m New Technology Telescope J-band natural-seeing image centred on σ Ori Aa,Ab,B; approximate size is 150 x 150 arcsec². The brightest stars of the Trapezium-like system are labelled. Right: AstraLux Norte/2.2 m Calar Alto z'-band lucky image roughly centred on σ Ori E; size is 6.0 x 6.0 arcsec². In both images, north is up and east is left. Note the very small size AstraLux field of view with respect to the SofI one.
FIG. 2

Limit of our *AstraLux Norte* z’-band image: magnitude difference $\Delta z'$ as a function of angular separation $\rho$ to $\sigma$ Ori E (2.5% best frames). The vertical dotted lines indicate the expected location of the candidate companion to $\sigma$ Ori E, at $\rho = 0.33 \pm 0.03$ arcsec.