Tracing the Dynamic Orbit of the Young, Massive High-eccentricity Binary System θ^1 Orionis C. First results from VLTI aperture-synthesis imaging and ESO 3.6-metre visual speckle interferometry

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Located in the Orion Trapezium Cluster, θ^1 Ori C is one of the youngest and nearest high-mass stars known. Besides its unique properties as an oblique magnetic rotator, the star happens to be a close (~20 milliarcseconds) binary system, which makes it an ideal laboratory to determine the fundamental parameters of young hot stars. In this article, we report on our 11-year interferometric monitoring campaign, which covers nearly the full dynamic orbit of the system and resulted in the first interferometric images obtained with the VLT interferometer (VLTI) in the infrared (~20 µm) and diffraction-limited bispectrum speckle interferometry at the ESO 3.6-metre telescope at visual (440 nm) wavelengths.

The formation and early evolution of high-mass stars is still a matter of ongoing debate. In particular, for young O-type stars, stellar evolutionary models are still highly uncertain and require further empirical verification. In order to test and refine these models, perhaps the most important parameter is the stellar mass, which, together with the chemical composition and the angular momentum, determines the entire stellar evolution. Thus, direct and unbiased mass estimates, such as those provided by the dynamical masses accessible in binary systems, are very important to advance our knowledge about the earliest phases of stellar evolution.

Due to its relative proximity at just ~400 pc, the Orion Nebula Cluster (ONC) is the best-studied star-forming region where high-mass stars are forming. θ^1 Ori C in the Orion Trapezium is the brightest and most massive (~40 $M_\odot$) of the ONC members and has been the target of numerous studies. With an age of less than one million years, this O7V-type star is also one of the youngest O-type stars known in the sky, and its strong Lyman radiation dominates the whole Orion Nebula. θ^1 Ori C also illuminates the proplyds and shapes its environment by strong stellar winds. Furthermore, θ^1 Ori C is one of only two O-stars with a detected magnetic field (the other one being the much more evolved object HD 191612). The strong magnetic field (1.1 ± 0.1 kG, Donati et al., 2002) might also channel the radiation-driven winds from both hemispheres along the magnetic field lines to the equatorial plane, where the winds collide at high velocity, forming a thin, nearly stationary shock region in the equatorial plane. This "magnetically confined wind shock" (MCWS) model (Babel & Montmerle, 1997) can explain not only the hard X-ray emission from θ^1 Ori C, but also the periodic variability of the Hα line, several UV spectral lines, the X-ray flux, as well as the magnetic field (see Stahl et al., 2008, for a brief review).

In 1997, near-infrared bispectrum speckle observations obtained with the Russian BTA 6-metre telescope revealed a visual companion around θ^1 Ori C (Weigelt et al., 1999), contributing about 30% of the total flux at visual to near-infrared wavelengths. The discovery of this very close companion star situated at 33 milliarcsecond (mas) offset is important, since the observation of orbital motion allows one to derive direct constraints on the stellar masses as well as the dynamical distance to the Orion Trapezium Cluster. While stellar mass measurements are urgently required for the calibration of stellar evolutionary models of O-type stars, distance estimates are of general importance for all studies on the ONC star-forming region. An interesting aspect of the dynamical history of the ONC was presented by Tan (2004), who proposed that the Becklin–Neugebauer (BN) object, which is located 45" northwest of the Trapezium stars, might be a runaway B star ejected from the θ^1 Ori C multiple system about 4000 years ago. Although still a matter of ongoing debate, this scenario is based on proper motion measurements, which show that the BN object and θ^1 Ori C recoil roughly in opposite directions. Therefore, a high-precision orbit measurement of θ^1 Ori C might offer the fascinating possibility of recovering the dynamical details of this recent stellar ejection.

Diffraction-limited imaging at 440 nm

Bispectrum speckle interferometry is a powerful technique to overcome atmospheric perturbations and to reach the diffraction-limited resolution of ground-based telescopes. In contrast to adaptive optics, which currently only provides a good Strehl ratio at near-infrared wavelengths, bispectrum speckle interferometry can provide diffraction-limited images even at visual wavelengths. Since the discovery of the θ^1 Ori C companion in 1997, we have employed the BTA 6-metre telescope to trace the orbital motion of the system at near-infrared (*J*-, *H*- and *K*-bands) and visual wavelengths (*V*-band). In January 2008, we also used our visitor speckle camera at the ESO 3.6-metre telescope on La Silla and obtained diffraction-limited images of θ^1 Ori C even at a wavelength of 440 nm (*B*-band; see Figure 4). In spite of the small binary separation of 20 mas, the astrometry could be measured with an accuracy of better than 3 mas, which is approximately a factor of ten smaller than the diffraction-limited resolution of the 3.6-metre primary mirror at this wavelength. With 3.6-metre-class telescopes such as the ESO 3.6-metre or the NTT, this technique allows one to obtain diffraction-limited images of targets brighter than K ~ 14 mag or V ~ 17 mag, with a typical observing time of 1 hour per target/calibrator pair (including overheads). Given these favourable characteristics, bispectrum speckle interferometry is also a very promising technique for 8-metre-class telescopes such as the VLT, likely enabling diffraction-limited imaging with an angular resolution down to ~11 mas (*B*-band).

VLTI/AMBER high accuracy astrometry

Of course, even higher angular resolution can be achieved with long-baseline interferometry. Combining the light of separate apertures, infrared interferometers, such as the VLTI, can now provide a resolution corresponding to the separation of the individual apertures in an array of telescopes. The VLTI near-infrared beam combination instrument AMBER (Petrov et al., 2007) combines this revolutionary technique with spectral capabilities, allowing the measurement of the interferometric observables (visibility and closure phase) as a function of wavelength.

Adding the spectral information can open up unique new science applications (for instance, by performing long-baseline interferometry in spectral lines) and can also increase the observing efficiency by sampling radial tracks of the Fourier plane (uv-plane) with each observation. This effect is illustrated in Figure 1, where we show the uv-coverage of a single AMBER observation taken in low spectral resolution mode (LR-mode, $\lambda/\Delta\lambda = 35$) together with the expected wavelength-differential visibility and closure phase signatures of a binary star. In Figure 2 we show actual VLTI measurements obtained on θ^1 Ori C, revealing the expected wavelength-differential signatures. These wavelength-differential signatures can then be fitted to geometric models, which allowed us to derive the binary astrometry with a very high precision of ~0.5 mas. As a matter of fact, the astrometric precision achievable with AMBER's LR-mode is currently not limited by the interferometric constraints, but by the precision with which the instrument wavelength calibration can be performed.

Model-independent VLTI aperture-synthesis imaging

To date, model-fitting, as described above, represents the most commonly applied approach to extract scientific information from infrared interferometric data. Of course, this approach requires some *a priori* knowledge about the source structure, which allows the astronomer to choose an appropriate geometric or physical model. In many cases, this information might not be available (or could potentially be biased), which makes it highly desirable to enable optical interferometers, such as VLTI/AMBER, to directly recover the source brightness distribution without any model assumptions. Although the principles of interferometric imaging through closure phases are practically identical to the ones routinely applied in radio interferometry, optical interferometry faces additional challenges, which are mainly related to the very small number of telescopes combined in current-generation optical interferometers and in the resulting poor uv-plane coverage.

Given that our VLTI/AMBER observations on θ^1 Ori C (including 18 measurements on one Unit Telescope triplet and three Auxiliary Telescope (AT) triplet configurations) provide a relatively good coverage of the uv-plane, we applied our image reconstruction algorithm (Building Block Mapping; Hofmann & Weigelt, 1993) to reconstruct a model-independent aperture-synthesis image. The reconstructed image (Figure 3) shows the θ^1 Ori C system with a resolution of ~2 mas and independently confirms the binary astrometry determined by model-fitting.

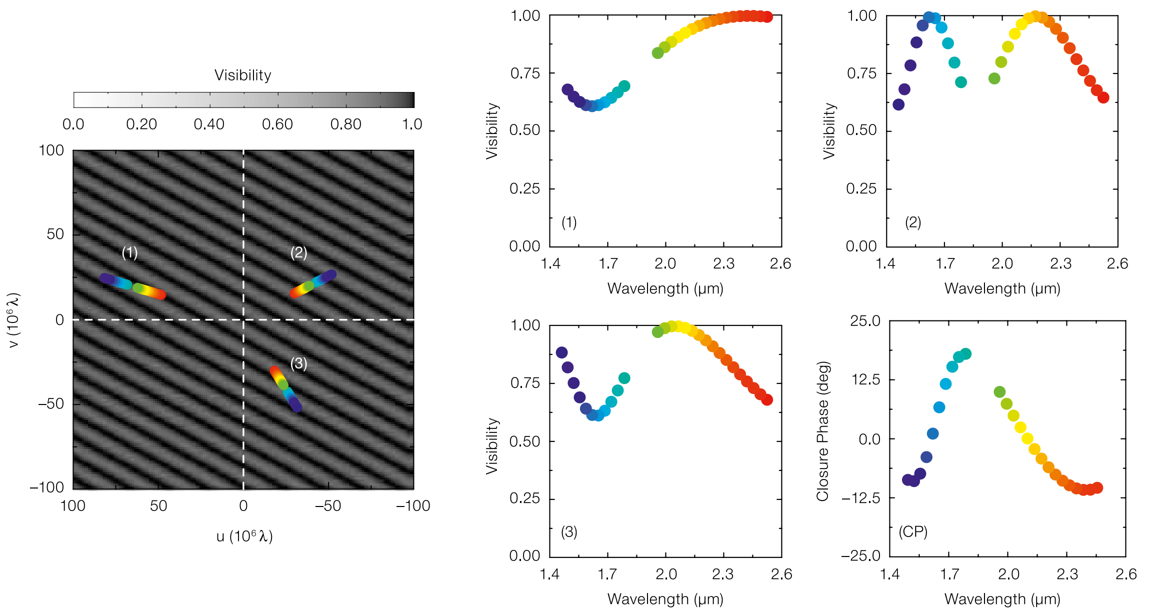

Figure 1. VLTI/AMBER three-telescope spectro-interferometry allows one to cover simultaneously the *H*- and *K*-band spectral window, resulting in radial tracks in the uv-plane (left). These radial tracks allow one to sample the sinusoidal visibility and closure phase modulation expected for a binary star, such as θ^1 Ori C with a single AMBER observation (middle and right columns).

The dynamic orbit of the θ^1 Ori C system

Including earlier astrometric measurements obtained with bispectrum speckle interferometry (Weigelt et al., 1999; Schertl et al., 2003; Kraus et al., 2007) as well as IOTA (Kraus et al., 2007) and NPOI (Patience et al., 2008), the available data covers the period from 1997 to 2008 and shows that since its discovery, the binary system has nearly completed a full orbit cycle (Figure 4). The good orbital coverage allows us to solve for the astrometric orbit of the system, yielding a short-period (P ~ 11.2 yrs), high-eccentricity (e ~ 0.6) orbit. According to this orbit solution, the physical separation between the two high-mass stars varies between ~ 7 AU at periastron passage and 28 AU at apastron. From the orbital elements, we derived constraints on the system mass (M1 + M2 = 47 ± 4 $M_\odot$) and on the distance to the ONC (410 ± 20 pc; see Kraus et al. [2009] for a description of the applied methods). Our distance estimate is in excellent agreement with recent trigonometric parallax measurements of some Orion non-thermal radio emitters, which yielded a distance of 414 ± 7 pc (Menten et al., 2007).

Various earlier spectroscopic studies also measured the radial velocity of θ^1 Ori C, revealing long-term radial velocity variations (Stahl et al., 2008). Combined with our solution for the astrometric orbit, these radial velocity measurements can be used to constrain the mass ratio of the two stars to M2/M1 = 0.23 ± 0.05. Accordingly, the individual stellar masses are ~ 39 $M_\odot$ and ~ 8 $M_\odot$, corresponding to spectral types of O5.5 and B2, respectively.

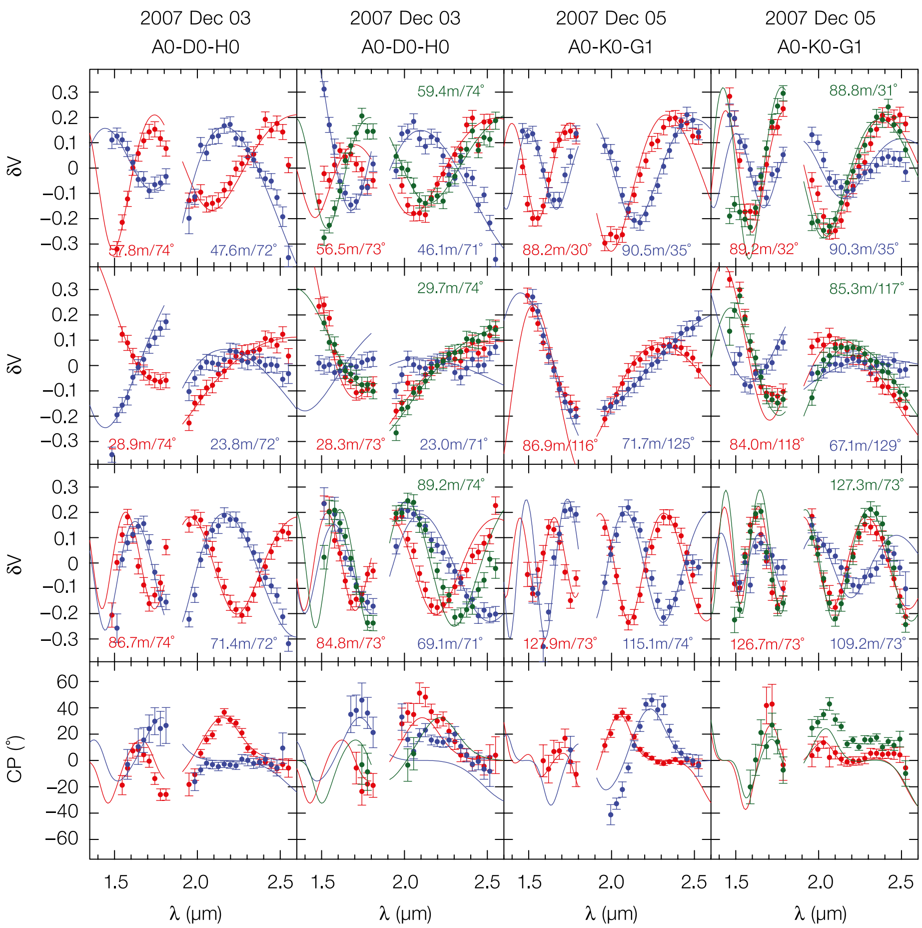

Figure 2. VLTI/AMBER data obtained on θ^1 Ori C during two half-nights in December 2007 (points), overlaid with our best-fit binary model. The upper three rows show wavelength-differential visibilities, while the bottom row shows the recorded closure phases.

Future science prospects

Being well suited to high-accuracy mass estimates, the θ^1 Ori C binary system represents an important benchmark for evolutionary models of young massive stars. Interferometric as well as spectroscopic observations over the next few years will be important to tighten the observational constraints further, in particular as the system is approaching the next periastron passage around 2013.9.

Other very exciting science could perhaps be achieved in the immediate future using AMBER's higher spectral resolution modes ($\lambda/\Delta\lambda$ = 1500 or 12 000). These modes will allow one to spatially resolve the distribution of the line-emitting gas in the inner few stellar radii around the θ^1 Ori C primary star. According to the MCWS model, this line emission traces the magnetically channelled stellar winds, providing unique insights into the mass-loss mechanism and the dramatic magnetohydrodynamic effects around this intriguing young hot star.

Our successful aperture-synthesis imaging of the θ^1 Ori C system demonstrates the capabilities of the VLTI/AMBER facility for high quality interferometric imaging. Considering the large number of exciting upcoming science applications which rely on model-independent imaging, these capabilities will be of utmost importance not only for AMBER but, in particular, for the second generation VLTI instruments. Given the large demand for observing time and the relatively small number of AT stations offered, interferometric imaging with the 3-telescope beam-combiner AMBER currently remains a challenging task. The second generation instruments GRAVITY, MATISSE and VSI will simultaneously combine four and more apertures, which should significantly increase the imaging efficiency and ultimately push interferometric imaging into mainstream astronomy.

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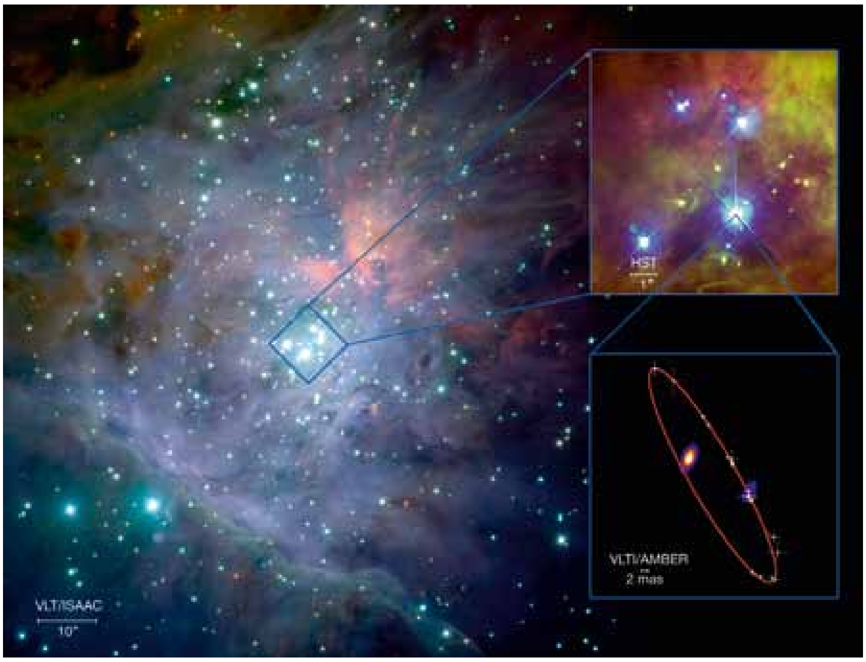

Figure 3. Mosaic showing the Orion Trapezium Cluster, as seen with VLT/ISAAC (left, from ESO/Mark McCaughrean) and with the HST (upper, from NASA/John Bally). The inset to the lower right shows our θ^1 Ori C VLTI/AMBER aperture-synthesis image (*K*-band, epoch 2007.9) and the derived orbit solution. At the given epoch (2007.9), the companion (flux ratio 1:4) had a separation of 19.07 ± 0.05 mas and was located towards position angle 241.2 ± 1°. The elongation of the stars reflects the limitations in the achieved uv-plane coverage.

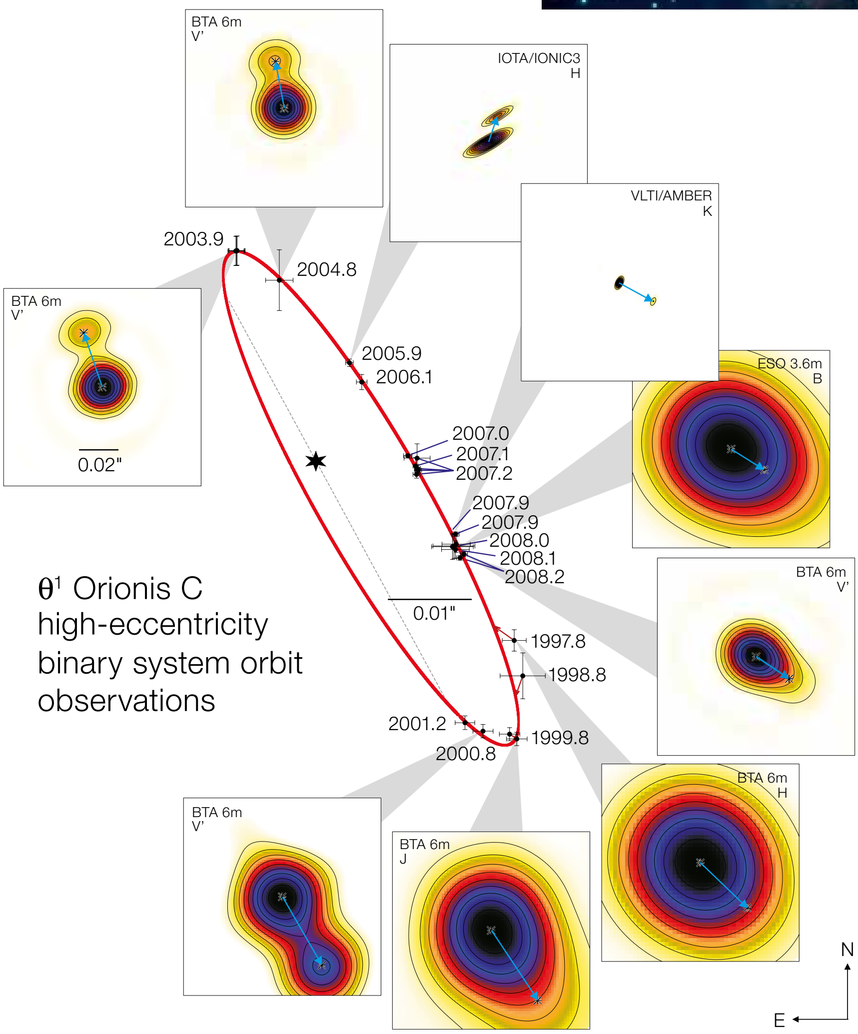

Figure 4. Dynamical orbit of the high-eccentricity binary system θ^1 Ori C, as derived from the interferometric monitoring campaign, covering the period 1997 to 2008.