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VLTI Imaging of a High-Mass Protobinary System: Unveiling the Dynamical Processes in High-Mass Star Formation

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High-mass stars exhibit a significantly higher multiplicity frequency than low-mass stars, likely reflecting differences in how they formed. Theory suggests that high-mass binaries may form by the fragmentation of self-gravitational discs or by alternative scenarios such as disc-assisted capture. Near-infrared interferometric observations reveal the high-mass young stellar object IRAS 17216-3801 to be a close high-mass protobinary with a separation of 0.058 arcseconds (~ 170 au). This is the closest high-mass protobinary system imaged to date. We also resolve near-infrared excess emission around the individual stars, which is associated with hot dust in circumstellar discs. These discs are strongly misaligned with respect to the binary separation vector, indicating that tidal forces have not yet had time to realign. We measure a higher accretion rate towards the circumsecondary disc, confirming a hydrodynamic effect where the secondary star disrupts the primary star's accretion stream and effectively limits the mass that the primary star can accrete. NACO *L*′-band imaging may also have resolved the circumbinary disc that feeds the accretion onto the circumstellar discs. This discovery demonstrates the unique capabilities of the VLTI, creating exciting new opportunities to study the dynamical processes that govern the architecture of close multiple systems.

There is strong observational support for the hypothesis that high-mass stars (> 10 $M_{\odot}$) can form through accretion from circumstellar discs (for example, Kraus et al., 2010; Boley et al., 2013; Johnston et al., 2015; Caratti o Garatti et al., 2017). These discs channel strong stellar winds and radiation in the polar direction, enabling the infall of material and allowing the star to grow beyond the limits imposed by radiation pressure and the classical Eddington barrier (for example, Kuiper et al., 2010).

While the detection of these discs is often interpreted as evidence for similarities between low- and high-mass star formation, it is also important to emphasise that the monolithic collapse scenario that has been developed for low-mass star formation is unable to explain the differences in multiplicity fractions observed between low-mass and high-mass stars. Surveys have found that ≥ 90 % of all O-type stars (> 16 $M_{\odot}$) are close multiple systems, while this fraction drops to 20 % for A-type stars (~ 3 $M_{\odot}$; Chini et al., 2014). In addition, the number of companions increases with the mass of the primary star. Various dynamical scenarios have been proposed to explain these remarkable characteristics. For instance, high-mass multiples might form via the fragmentation of self-gravitating discs (Kratter & Matzner, 2006), disc-assisted capture (Bally & Zinnecker, 2005), or through failed mergers in stellar collisions (Dale & Davies, 2006). Mass transfer processes during the early formation phase or dynamical three-body capture might also lead to the formation of close binaries of near-equal mass.

Testing these scenarios requires the discovery of high-mass protobinaries that are still in the process of forming. Given the large (kiloparsec) distance to these objects and their embedded nature, such studies need to be conducted at infrared or submillimetre wavelengths and at the highest achievable angular resolution. With its unprecedented 0.002-arcsecond angular resolution, the VLT Interferometer (VLTI) is well-suited to make such observations. In order to search for protobinary systems and to obtain new insights into the disc structure of high-mass young stellar objects (YSOs), we initiated an interferometric survey in the *K*-band using the Astronomical Multi-BEam combineR (AMBER) on the VLTI. The goal was to study the astronomical unit scale inner environment around high-mass YSOs at low spectral resolution (*R* = 35). The first results from this campaign were published in Kraus et al. (2010), where we detected an au-scale disc around the high-mass YSO IRAS 13481-6124.

GRAVITY and AMBER aperture synthesis imaging

Another source in our sample, IRAS 17216-3801, is a high-mass YSO located at a distance of 3.1 ± 0.6 kpc (Boley et al., 2013) with a bolometric luminosity of 6.1 × 10^4 $L_{\odot}$. Our VLTI observations resolve the system into a binary with a separation of 58 milliarcseconds (mas), corresponding to approximately 170 au at the distance of the source (Kraus et al., 2017). We estimate the component masses as 20 and 18 $M_{\odot}$, which makes the system about three times more massive and five times more compact than previously imaged high-mass multiple systems (for example, Sridharan et al., 2005). Most importantly, the mas-scale resolution achieved with the VLTI allows us to spatially resolve the discs around the individual components, which is the first time that this has been achieved for a high-mass protobinary system.

AMBER measurements taken in 2012 using the long Unit Telescope (UT) baselines (30–130 m) showed strong visibility and closure phase modulations that are characteristic of multiple systems, while the low visibility level indicated the presence of both disc and photospheric emission. As part of a VLTI GRAVITY Science Verification programme, we obtained medium spectral resolution (*R* = 500) on complementary Auxiliary Telescope (AT) baselines (11–34 m). The GRAVITY data recording sequence on IRAS 17216-3801 required less than one hour, but resulted in interferometric observables that changed dramatically on timescales of minutes (Figure 1), reflecting the changes in projected baselines that resulted from the Earth's rotation. The rapid changes in the visibility and phase signal allow us to constrain the object's structure with relatively little observing time.

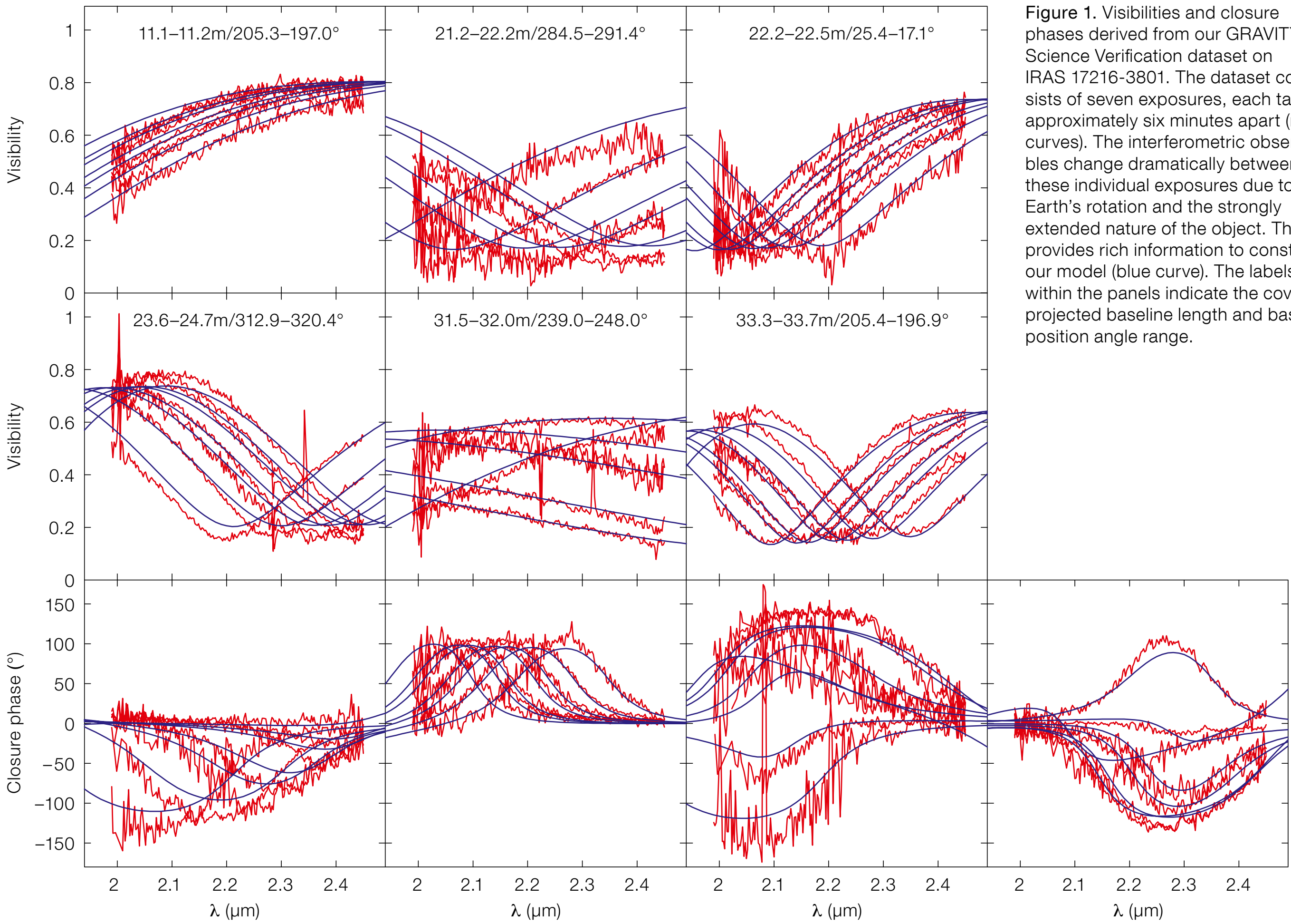


Figure 1. Visibilities and closure phases derived from our GRAVITY Science Verification dataset on IRAS 17216-3801. The dataset consists of seven exposures, each taken approximately six minutes apart (red curves). The interferometric observables change dramatically between these individual exposures due to the Earth's rotation and the strongly extended nature of the object. This provides rich information to constrain our model (blue curve). The labels within the panels indicate the covered projected baseline length and baseline position angle range.

The combined GRAVITY and AMBER data provide adequate uv-plane coverage for image reconstruction. In order to combine the two datasets, we needed to account for the orbital motion of the binary between 2012 and 2016. We therefore implemented an algorithm that rotated and scaled the uv-plane such that it compensated for the orbital motion between the two epochs, where the changes in binary separation and binary position angle were fitted as free parameters during the image reconstruction and model-fitting process. This method indicates that the separation remained constant between 2012 and 2016, while the binary position angle changed by 8° in the same time period.

Figure 2 (left) depicts the system at the 2016 epoch and clearly reveals a binary with 57.9 ± 0.2 mas separation (170 au at 3.1 kpc). Both components are associated with spatially resolved emission, where the emission around the northern component (A) is more extended than around the southern component (B) and also clearly misaligned with respect to the binary separation vector. In order to characterise this extended emission, we fitted an analytic model to the visibility and closure phase data, which includes the photospheric emission from the stars and the discs around each star, and the extended emission is represented with a Gaussian component. We parameterised the discs with a radial temperature power law, where the disc emission extends between an inner and outer radius. Our model indicates that the circumprimary and circumsecondary discs are seen under intermediate inclination angles (60° ± 10° and 38° ± 10°, respectively, where 0° corresponds to face-on viewing geometry). The circumsecondary disc is roughly aligned (position angle 159° ± 15°) with the binary separation vector of 166.8° ± 0.2°, while the circumprimary disc is strongly misaligned (position angle 67° ± 7°; see sketch in Figure 2, right).

Both discs seem to feature an opacity hole in the inner regions at radii of 2.77 ± 0.39 mas (circumprimary disc) and 2.49 ± 0.42 mas (circumsecondary disc). This is a well-known effect in low- and intermediate-mass YSOs (for example, Lazareff et al., 2017) and has also been observed in the high-mass YSO IRAS 13481-3601 (Kraus et al., 2010). The derived inner disc radii likely indicate the region close to the star where the temperatures are too high for dust grains to exist.

NACO imaging and a potential circumbinary disc

We also imaged the system using NACO adaptive optics imaging in several near-infrared filters (including a *J*-band filter and narrow-band filters in *H* and *K*). When

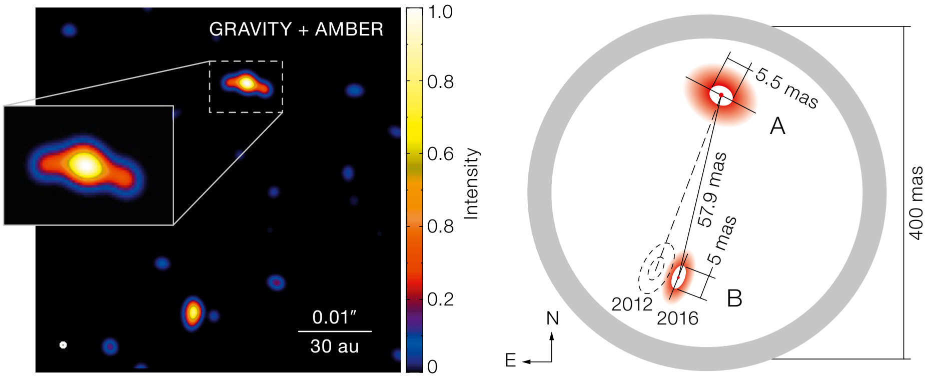
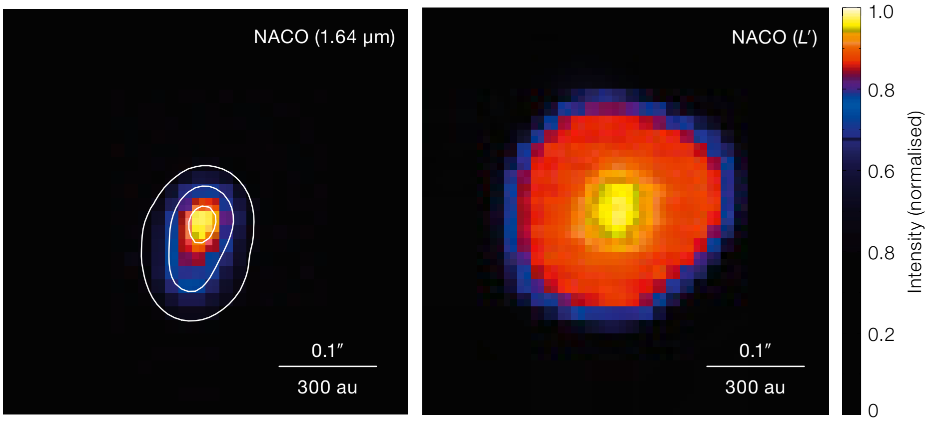


Figure 2. Far left: Aperture synthesis image reconstructed from our GRAVITY (AT) and AMBER (UT) datasets. Left: Sketch of the IRAS 17216-3801 system, as derived with model-fitting techniques.

comparing these images with the point spread function (PSF) measured on a dedicated PSF calibrator star, there is a clear "notch" south of the primary star, indicating that we marginally resolve the 58 mas binary also with NACO (1.64 µm image in Figure 3, top-left and bottom panels).

In another image taken with the *L*′-band filter, we detect a surprisingly extended structure with a half width at half maximum (HWHM) size of ~ 250 mas (Figure 3, top-right and bottom). Hydrodynamic simulations predict that a binary should truncate the circumbinary disc at about three times the binary semi-major axis. Using the measured separation as a lower limit for the binary semi-major axis, we expect the circumbinary disc to extend to ≥ 175 mas, which is broadly consistent with the measured size of the *L*′-band structure. As no dedicated PSF star observations have been obtained with this filter, new observations will be required in order to confirm this finding and to better characterise the *L*′-band geometry.



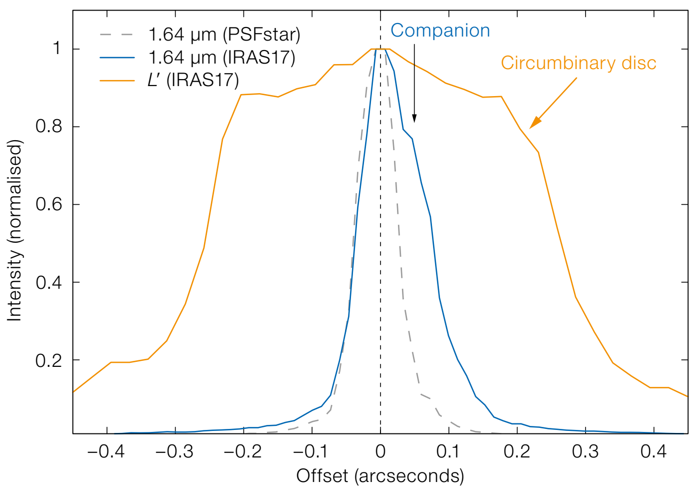


Figure 3. Top: NACO images of IRAS 17216-3801 taken with a 1.64-µm narrow-band filter and the *L*′-band filter. Left: Radial cut along the binary separation vector, overplotted with the PSF measured on a calibrator star in the 1.64-µm filter.

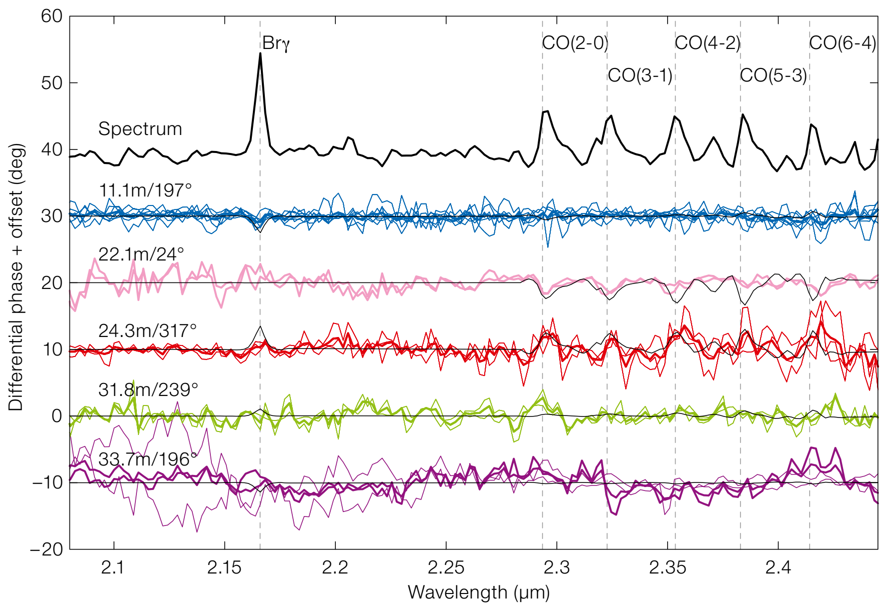
Insights into the dynamical history of IRAS 17216-3801

To our knowledge, this study marks the first time that the circumstellar discs of a high-mass protobinary system could be spatially resolved. We find that the circumstellar discs are strongly misaligned with respect to the binary separation vector, which provides insight into the dynamical history of the system.

Theoretical studies have uncovered various formation mechanisms that could result in misaligned discs, including the fragmentation of self-gravitating discs, perturbation by a third body, or infall of material whose angular momentum vector was misaligned to that of the gas from which the binary initially formed (Bate et al., 2010). However, once a highly misaligned system has formed, tidal interactions will work towards realigning the discs. This realignment should happen on the viscous timescale (Papaloizou & Terquem, 1995) or on the much shorter precession timescale (Bate et al., 2000). Based on our estimates of the individual stellar masses and of the outer disc radii, we derive an upper limit on the precession timescale of ~ 200 000 years for the circumprimary disc and ~ 900 000 years for the circumsecondary disc. Our observations therefore suggest that tidal realignment is still ongoing, indicating the young dynamical age of the IRAS 17216-3801 system.

Tracing accretion onto the individual components

Our GRAVITY observation also covers spectral lines corresponding to the Brγ 2.16 µm hydrogen recombination line and CO bandheads between 2.3–2.4 µm. This allows us to determine whether



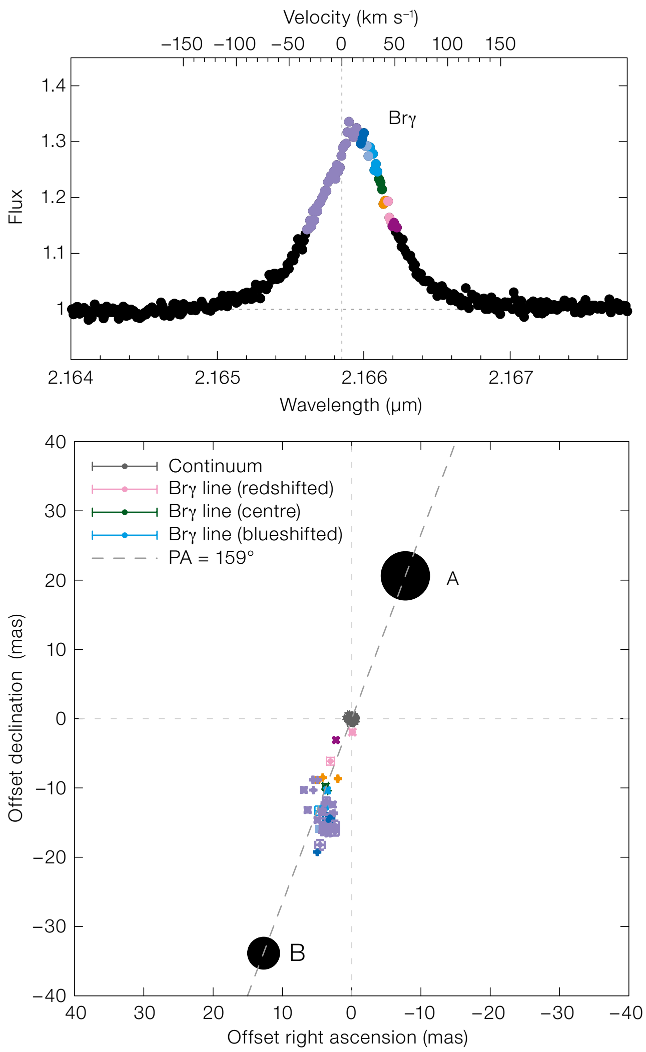


Figure 4. Above: Spectrum and wavelength differential phases measured with GRAVITY. We constrain the Brγ and CO bandhead line-emitting region (black curves) and find that Brγ is associated with a region very close to the stars, while the CO emission originates from gas located between both sources. Left: CRIRES spectrum of the Brγ line (top) and the derived continuum-corrected spectro-astrometric photocentre displacements (bottom). Together with the knowledge of the continuum geometry obtained with the VLTI, these photocentre displacements allow us derive the Brγ contributions and accretion rates of the individual components.

these lines are associated with the primary star, secondary star, or the extended environment. We measure non-zero wavelength differential phase signals and visibility signals that are distinctly different for the Brγ line and the CO bandhead emission (Figure 4, left), indicating that they originate in different regions of the circumstellar environment.

The CO bandheads are believed to trace warm (> 10^3 K) neutral gas. We find that the CO line emission is spatially extended and comes from a region between the two stars. This suggests that the molecular emission might trace extended gas streams between the two discs, opening up the exciting prospect of imaging these gas streams with future GRAVITY observations at better uv-coverage.

The Brγ line, on the other hand, traces hot (> 10^4 K) ionised gas and reveals both mass accretion and ejection processes (for example, Kraus et al., 2008; Kurosawa et al., 2016; Caratti o Garatti et al., 2016). For IRAS 17216-3801, we find that the line emission originates from compact regions close to the individual stars, where 60 % of the Brγ emission is associated with the secondary star, while only 40 % is associated with the primary. This is also confirmed by an independent measurement we obtained in 2012 in parallel to the AMBER observations of the source using the CRyogenic InfraRed Echelle Spectrometer (CRIRES). CRIRES spectra (R = 100 000) were obtained with three different slit orientations, allowing us to constrain the spatial origin of the line emission using the spectro-astrometry technique. In the bottom panel of Figure 4 we overplot the Brγ-line photocentre offsets (measured relative to the continuum photocentre after continuum correction) with the position of the stellar components at that epoch. The Brγ photocentre offsets are located between the two stars, but are more closely clustered towards the secondary. Both stars therefore contribute to the line emission, although the secondary contributes a significantly larger fraction (62 %) to the total line flux than the primary (48 %), confirming the values that we found independently with GRAVITY.

The higher Brγ flux measured towards the lower-mass secondary star indicates that it accretes at a higher rate than the primary. This might seem counter-intuitive at first. However, hydrodynamic simulations predict that close companions disrupt the accretion stream onto the primary and channel most of the infalling material onto the circumsecondary disc, effectively limiting the mass that the primary can accrete (Bate & Bonnell, 1997). Our GRAVITY and CRIRES observations of IRAS 17216-3801 provide some tantalising first observational evidence of this effect.

Future outlook

The discovery of the IRAS 17216-3801 binary system and the unique capabilities of the VLTI open up exciting new opportunities to study dynamical interaction in high-mass protobinary systems and to characterise the physical conditions in circumstellar discs and circumbinary discs. There is a strong need to discover additional high-mass protobinary systems in order to build a statistically significant sample. This will allow us to explore the relation between binary properties (for example, separation and mass ratios) and the resulting disc structure, enabling a better understanding of the role of multiplicity in high-mass star formation.

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References

Bate, M. R. & Bonnell, I. 1997, MNRAS, 285, 33
Bate, M. R. et al. 2000, MNRAS, 317, 773
Bate, M. R. et al. 2010, MNRAS, 401, 1505
Boley, P. et al. 2013, A&A, 558, 24
Caratti o Garatti, A. et al. 2016, A&A, 589, L4
Caratti o Garatti, A. et al. 2017, Nature Physics, 13, 276
Chini, R. et al. 2012, MNRAS, 424, 1925
Dale, J. E. & Davies, M. B. 2006, MNRAS, 366, 1424
GRAVITY Collaboration 2017, A&A, 602, A94
Johnston, K. et al. 2015, ApJ, 813, 19
Kratter, K. M. & Matzner, C. D. 2006, MNRAS, 373, 1563
Kraus, S. et al. 2008, A&A, 489, 1157
Kraus, S. et al. 2010, Nature, 466, 339
Kraus, S. et al. 2017, ApJL, 835, L5
Kuiper, R. et al. 2010, ApJ, 722, 1556
Kurosawa, R. et al. 2016, MNRAS, 457, 2236
Lazareff, B. et al. 2017, A&A, 599, L85
Papaloizou, J. C. B. & Terquem, C. 1995, MNRAS, 274, 987
Sridharan, T. K., Williams, S. J. & Fuller, G. A. 2005, ApJL, 631, L73

Enrico Sacchetti/ESO

The Very Large Telescope Interferometer Delay Lines.