Massive Stars Near and Far
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Constraining the behaviour of the young massive stars through interferometry

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Abstract. The formation of multiples has seen some significant progress over the past years mainly due to the advent and the expansion of high-angular resolution facilities. Star-forming regions are the laboratories where massive stars can be caught right after their formation phase. Still, the observational constraints and the properties of young multiple systems are poorly documented. These proceedings contain recent results about the multiplicity properties of six young O-type stars in the M17 star-forming region, observed by the means of near-IR interferometric observations, which have provided insight into the origin of massive close binaries in a cluster environment.

Keywords. stars: pre–main-sequence, (stars:) binaries (including multiple): close, stars: formation, instrumentation: high angular resolution, techniques: interferometric

1. Introduction

Our knowledge about high-mass star ($M_i > 8\mathrm{M}_\odot$) formation is undoubtedly growing as a result of both observational and numerical efforts, even though unknowns are persisting. In addition to a rapid formation process ($\sim 10^5$ yrs, Tan et al. 2014), young massive stars are highly reddened with a spectral energy distribution peaking in the mid- to far-infrared (IR) and they form in dusty natal clouds that emit light at low frequency (Zinnecker & Yorke 2007). High-resolution, long-wavelength observations are thus necessary to detect forming stars. Also, physical processes involved in the formation of multiple stars span a large dynamic range, from ∼1 au to dozens of pc. Consequently, the theoretical developments for multiple formation supersede the observational constraints.

Current multiplicity constraints: To date, only OB stars of a few Myr benefit from well characterised multiplicity properties. It is now unanimously acknowledged that the majority of massive stars experience interactions with (at least) a companion during their life, a fact that has strong repercussions on their final fate (Sana et al. 2012; Moe & Di Stefano 2017). The multiplicity distribution evolves during the lifetime of the system and might be altered through dynamical interactions. In itself, the multiplicity distribution measured among well formed massive stars do not necessarily reflect the primordial multiplicity (Offner et al. 2022). Constraining the true end product of massive multiple formation requires observations of very young (< 1Myr) massive star-forming regions.

Lack of short-period binaries in young clusters: It has been recently observed that 1D velocity dispersions of massive stars in young clusters increases as they get older

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(Ramírez-Tannus et al. 2021). In other words, they observe an increase in the fraction of close binary systems as the clusters evolve. With its very young age (<1Myr), the M17 high-mass star forming region is no exception to the rule. The analysis of 11 massive pre/near-main-sequence stars, revealed a low radial-velocity dispersion ($\sigma_{1D} = 5.6 \pm 0.2$ km s^{-1}, Sana et al. 2017), corresponding to a binary fraction of $f_{bin} = 0.12$, in stark contrast to that of fully formed main-sequence massive stars ($f_{bin} = 0.70$).

This intriguing lack of short-period binaries in one of the youngest populations of massive stars questions the formation processes leading to close binaries. Sana et al. (2017) and Ramírez-Tannus et al. (2021) put forward the migration scenario in which massive binaries are originally formed at large separations (100 $R_\odot$ or more) and harden on a time-scale of about 1.5 Myr. A strong evidence for this (almost) unexplored scenario is the presence of a significant number of relatively massive companions at separations corresponding to the expected size of the accretion disk (10-1000 au).

In this contribution, I make use of VLTI/GRAVITY observations of six young O stars (presumably single massive stars) in M17 and show that all the objects have at least one detectable companion in the 1-100 mas range, providing a new datapoint for the multiplicity of pre-main-sequence massive stars. I also discuss the separation range of the companions and explore the most likely channels for the formation of the host system.

2. Multiplicity among M17 massive objects

The VLTI/GRAVITY K-band instrument meets the optimal properties (near-IR wavelengths, high-angular resolution and sensitivity) for the search of companions around massive stars. The observational campaign targeted six pre-main-sequence O stars in the M17 star-forming region, known to be one of the youngest, closest and most luminous massive star nursery. The sample counts a modest amount of 6 objects as they were the brightest young massive stars in the region, with $K-$bands ranging from 7 to 9.3, reaching the limits of the GRAVITY+MACAO capabilities.

The main interferometric observables, the visibility amplitudes and closure phases were modelled using the python module PMOIRED (Mérand 2022). Binaries produce two fringe packets that will overlap to produce a sinusoidal signal in the visibility amplitudes. The separation between the peaks relates to the binary separation while the minimum visibility provides a measurement of the flux ratio between components. The closure phases are sensitive to the structure of the source and in particular to the asymmetries in the source distribution (different brightnesses, presence of an asymmetric circumstellar or -binary disk). A variety of models has been explored for each source, iteratively increasing the multiplicity order (single, binary, triple...) and complexity (fully resolved component, circumstellar disk). We infer the mass of the objects comparing the calibrated $K-$band spectra to a family of atmosphere models and evolutionary tracks (the full method can be found in Bordier et al. 2022).

Multiplicity and Companion fraction: The first direct derivable parameters from the analysis of the data are the multiplicity frequency (MF) and the companion fraction (CF). They respectively measure the ratio of multiple systems and the ratio of companions to the sample size. Fig. 1 shows the multiplicity and companion fraction of main sequence stars as a function of the primary mass, regardless of their environment (cluster, association, field). The total MF in our sample of six O stars in cluster (M17) exceeds 94% at the 68%-confidence interval and CF$=2.3 \pm 0.6$. In other words, we found out that three O stars have a resolved companion (binaries) and the three others have two companions (triples) in the 1-100 mas separation range. We added 5 unresolved companions from the literature to the companions we detected with GRAVITY. These statistics are derived using a wide range of survey methods, still, the six systems observed in M17 attest to the accuracy of the MFs and CFs measured in other galactic regions for stars

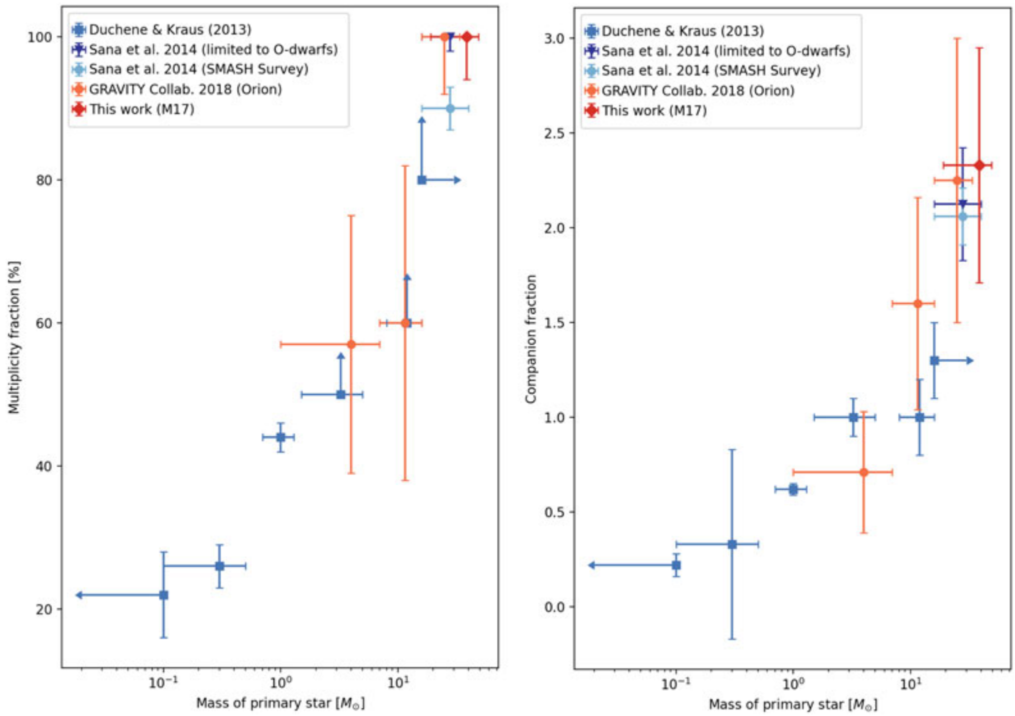

Figure 1. MF *(left)* and CF *(right)* measured with GRAVITY for the six O-stars in M17 as a function of the primary mass. For reference, values of Duchêne & Kraus (2013); Sana et al. (2014); Gravity Collaboration et al. (2018) are also presented for different mass ranges. The results from Sana et al. (2014) (SMASH Survey) presented here are those including companions up to 16000 au. Unresolved and resolved companions are taken into account in the final companion rate derived.

with $M > 20$ $M_\odot$. The young age of M17 and the cluster environment tends to show that massive star formation results in a multiple system with at least two companions on average.

We also display the separation distribution (a, assuming a distance of 1.7 kpc to M17) of all companions for different O-type star populations, all observed by the means of interferometry (see Fig. 2). This preliminary biased plot, shows a dearth of detections for companions within $a < 3$ mas and $\Delta mag > 2$, which are difficult sensitivities to reach with PIONIER and GRAVITY. We detect a handful of close binaries, with at least one companion below $a < 10$ au and wide binaries with $a > 10$ au.

3. Implications

Our results can be compared to the ones of Pomohaci et al. (2019) and Koumpia et al. (2021), two surveys targeting the multiplicity of massive young stellar objects (MYSOs) using K-band observations: high-contrast imaging for the former and interferometry for the latter. They highlight a multiplicity fraction of $31 \pm 8\%$ (>600 au) and $17 \pm 15\%$ (2-300 au) respectively. These results are interesting as they target the same class of objects but the statistics from Pomohaci et al. (2019) trace a different range of separations. The direct comparison might be biased due to the use of different techniques, non-uniform observations, sample size, mass ranges, physical distances and sensitivity limits. We highlight the fact that our targets are slightly older since they are suspected to have already reached the zero-age main-sequence. Still, it is difficult to attribute this

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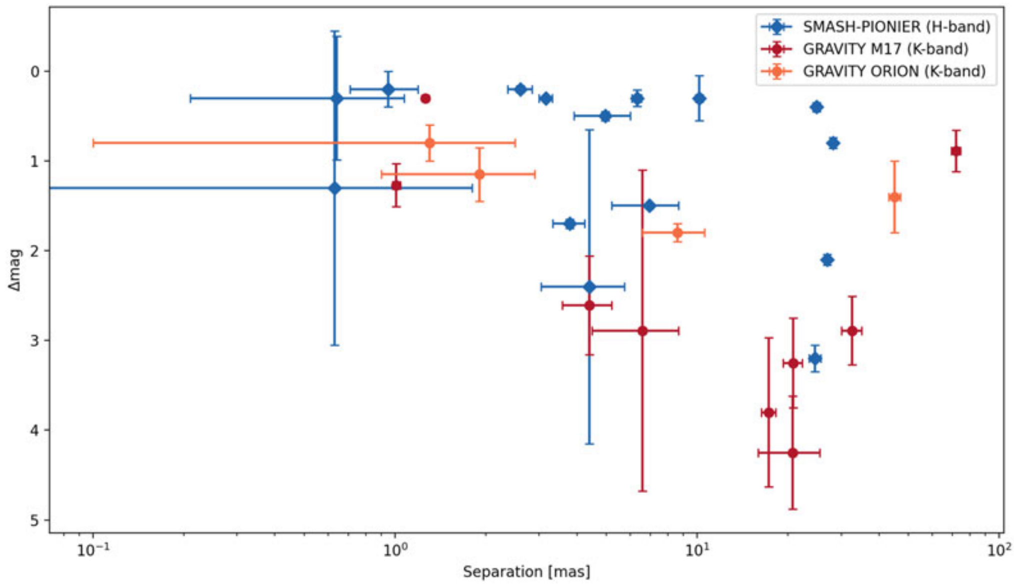

Figure 2. Magnitude difference (Δmag) per angular separation in mas. For reference, the 19 detected companions around O dwarfs as part of the SMaSH+ survey (blue; Sana et al. 2014) and the four resolved companions around high-mass stars in Orion (orange; Gravity Collaboration et al. 2018) have been plotted.

evident difference between the high MF derived in our study and the lower ones found by Pomohaci et al. (2019); Koumpia et al. (2021) to the above shortcomings. Taking all these limitations into consideration, our results (MF and CF) show more consistency with the results of Gravity Collaboration et al. (2018) and Sana et al. (2014) (limited to O-dwarfs), that are presented in Fig. 1.

Up to now, the most robust theories of multiple formation involve stellar migration, core accretion and fragmentation or disk fragmentation. The monolithic collapse involving core accretion and fragmentation would suggest that massive star formation is a scaled-up version of low-mass star formation. The best model would be the one reproducing the observed multiplicity statistics at birth and capable of forming very high-mass stars with tight companions when the systems reach the age of a few Myr. Meyer et al. (2018) and Oliva & Kuiper (2020) predict the formation of tight binaries with unequal components via disk fragmentation, in which early-stage companions have separations of tens of au to a couple of hundreds of au. To match the observed tight binaries (<1 au) in older populations, Ramírez-Tannus et al. (2021) show evidence for an inward migration of companions happening in $\sim$2 Myr, as a function of cluster age. The wide pairs may then harden and leave a tight binary behind. In the context of disk fragmentation theories, such an inward migration process may be driven by the interaction with the remnant of the accretion disk or with protostellar bodies within the cluster. Effects of migration on the binary period distribution will halt when the sinks of angular momentum disappear, i.e when disks and clusters disperse, or as other protostellar bodies are pushed to greater distances. Our findings fit with the predictions of disk fragmentation theories with regards to separations (<100 au) and the variety of systems (only 1 twin binary found). The presence of other companions within 100 au may support the migration channel where a third protostellar object pushes the first companion inward. Still, being about $\sim$1 Myr-old, the migration process inside M17 is likely underway: the wide range of separations

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and mass ratios might illustrate that the stellar population did not reach the expected time to form the final structures yet.

In order to confirm or discredit the striking high MF and CF found among this modest sample in M17, it is now important to conduct new observational campaigns of even younger protostars, targeting homogeneous samples and using similar observational techniques and sensitivities. A non-detection of companions within $\sim$200 au would point out a different behaviour and invalidate the proposed scenario.

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Discussion

?: Do you see any correlation between masses and separations?

EMMA BORDIER: We were not able to draw any conclusion on that respect. There is no clear trend for the companion mass according to the separation. We noticed that relatively massive companions are found around the primary stars regardless of their proximity to the host central star.

SILVIA TOONEN: It is very interesting to see this high fraction of triples directly in the observations. I was curious about their formation, are there any processes (regarding star formation) that are unique to triples/multiples, or can we look at it as forming a binary twice?

EMMA BORDIER: Indeed the formation process of such systems is still a subject of discussion. We discarded stellar mergers to form these high-mass stars as the M17 stellar density is too low. However, both the monolithic collapse and competitive accretion could work, even though they cannot straightforwardly result in what we observe, and there can be a mix of the 2 processes actually... For the companions themselves, disk fragmentation could be an explanation. Oliva et al. 2020 show that companions (2,3,4...) can be formed that way. Will they persist throughout the life of the central star, this is a mystery... We know that there is low chances for high-mass stars to form in isolation, so stellar-capture and dynamical interactions happening in the cluster could also be explored.

André OLIVA: I am wondering about the mass ratios of the companions. Are we talking about binaries/companions of similar masses or are the systems dominated by a primary surrounded by less-massive secondaries?

Emma BORDIER: Constraining the mass of the objects was not an easy task. We used the medium resolution spectra from GRAVITY and applied the flux ratio to the spectra to get the contribution of each star (primary and companions). Then we compared with evolutionary tracks and atmosphere models. This resulted in wide mass ratio ranges. For companions of about the same brightness to half of the brightness, we talk about similar masses and pretty close companions (<10 au). For the triples, the second companion is mostly farther and the flux ratio drops so in that case the central binary dominates in terms of mass. However, we expect massive binaries to be surrounded by outer low-mass companions. This is the purpose of my upcoming project with NACO data in which we aim at finding far, low-mass companions (1000 fainter than the primary and >800 au).

Kei TANAKA:

• Does the similarity between your M17 results and previous studies suggest close binary star formation by gas disks? Or small body interaction?

• For $\sim$1 mas systems, could you see the orbital motions in yr timescale? If so, it would be fun!

Emma BORDIER:

• From the fitting process, we could not model any circum-binary/stellar disk for example, meaning that there is no signature of a remnant disk. These stars have likely reached the ZAMS so they probably have blown out the material already. It would be interesting to look for the presence, dynamics and influence of the dust and gas surrounding the systems, for example by the means of ALMA. The fact that some systems are surrounded by an outer, smaller body would also be in favour of such interactions happening and supporting the migration of the first companion.

• We did not explore the orbital motions as there is only a single snapshot with GRAVITY but indeed it would be nice to monitor these objects and constrain the orbits (at least for the closest ones). We also had in mind to look for spectroscopic companions since for a couple of sources, there were no studies about the close environment.