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Multiple Star Systems in the Orion Nebula

GRAVITY Collaboration (see page 20)

GRAVITY observations reveal that most massive stars in the Orion Trapezium cluster live in multiple systems. Our deep, milliarcsecond-resolution interferometry fills the gap at 1–100 astronomical units (au), which is not accessible to traditional imaging and spectroscopy, but is crucial to uncovering the mystery of high-mass star formation. The new observations find a significantly higher companion fraction than earlier studies of mostly OB associations. The observed distribution of mass ratios declines steeply with mass and follows a Salpeter power-law initial mass function. The observations therefore exclude stellar mergers as the dominant formation mechanism for massive stars in Orion.

The formation of massive stars

The formation of massive stars remains a mystery. Hidden in their parental gas and dust clouds, it is unclear how their seeds can accrete so much matter before the repulsive forces from thermal pressure and radiation prevent the formation of a protostar. The most discussed scenarios are competitive accretion and core accretion (see, for example, Tan et al., 2014 and references therein). Another possibility is the collision of two stars, merging into a more massive star.

Core accretion is a scaled-up version of standard star formation applicable to stars similar to our Sun. In this scenario it is a single core that accretes its mass independently of other sibling cores. The mass of the star is then set at the beginning of the process, determined by the available mass in the accretion volume. An alternative explanation is formation by competitive accretion (for example, Tan et al., 2014), where several cores compete for the available mass, culminating in hierarchical systems with stars of different masses. Unlike in the core-accretion model, their masses are not pre-defined, but depend on the interaction with each other. A third possibility for the formation of massive stars is stellar mergers, where two colliding stars end up in a more massive object.

High angular resolution observations are crucial to pinning down the dominant mode of massive star formation. One of the closest massive star forming regions is the Orion Nebula Cluster, located at a distance of 414 ± 7 pc (for example, Reid et al., 2014). As such the Orion Nebula has been the target of many previous observations. The superb angular resolution and sensitivity of GRAVITY using the VLTI can reveal details on the crucial scales of 1–100 au, which had remained mostly unexplored until now.

Observations with GRAVITY

We observed the 16 brightest, most massive stars in the Orion Nebula Cluster, with masses between 2 and 44 $M_{\odot}$. The observations were mostly done with the Auxiliary Telescopes in astrometric configuration. Data were reduced with the standard GRAVITY pipeline (GRAVITY Collaboration, 2017). The interferometric data were then fitted to a binary star model, providing the flux ratio of the companion to the main star, and the separation vector between the two components (GRAVITY Collaboration, 2018).

We focused first on the central region, the Orion Trapezium Cluster, home of Orion's most massive, visible star, θ^1 Ori C. The 16 observed objects have a total of 22 companions; see Figure 1 for an overview.

With GRAVITY, we found three previously unknown companions and we confirm a suspected companion for ν Ori (Grellmann et al., 2013). The newly discovered stars belong to the systems of θ^1 Ori B, θ^2 Ori B, and θ^2 Ori C. We determined their separation, and from the flux ratio we could estimate the masses of all new companions (see GRAVITY Collaboration, 2018 for more details). θ^1 Ori B is a system of particular interest, as it consists of six objects in total. These objects are all gravitationally bound, though it is suspected that the system is only temporarily stable (Close et al., 2013). θ^1 Ori C is accompanied by two companion stars, one spectroscopic companion and one known companion with a determined orbit. With GRAVITY observations, we could refine the orbit of θ^1 Ori C_2 to have a period of 11.4 ± 0.2 yr and a semi-major axis of 18.2 ± 0.3 au. Additionally, we determined a new Orbit for θ^1 Ori D_2, with a semi-major axis of 0.77 ± 0.03 au and a period of 53.05 ± 0.06 days.

Most massive stars live in multiple systems

Massive stars are more often found in multiple systems than are lower mass stars. For example, Duchene & Kraus (2013) and Sana et al. (2014) found increasing numbers of stars in companion systems with higher stellar mass. Additionally, the average number of companion stars increases with higher mass. Our observations confirm this trend and our results are comparable to those of Sana et al. (2014). Orion's O-type stars have an average of 2.3 ± 0.3 companions.

Plotting the number of all our observed stars and their companions against stellar mass, we find the mass function well described by a power law with an exponent of $\Gamma = 1.3 \pm 0.3$ (Figure 2). This matches the initial mass function (IMF) for field stars (see, for example, Salpeter, 1955).

To constrain star formation scenarios, we compare predictions to our observations. For both core accretion and competitive accretion, the number of stars in companion systems and the number of companions should rise with mass (Clarke, 2001). Therefore, both scenarios would match our observations. The situation is different for the correlation between the companion masses. While competitive accretion shows no clear correlation between the primary and secondary mass, with a mass distribution that could follow a Salpeter IMF (for example, Tan et al., 2014) or a top-heavy companion mass distribution (Bate, Bonnell & Bromm, 2002), core accretion results in a strong correlation between the companion masses, which we do not observe. Also, the companion separation should correlate with system mass for core accretion. For competitive accretion, the separation should inversely correlate with system mass (Bonnell & Bate, 2005). In Orion, we observe no correlation between separation and system mass (Figure 3), which is inconsistent with

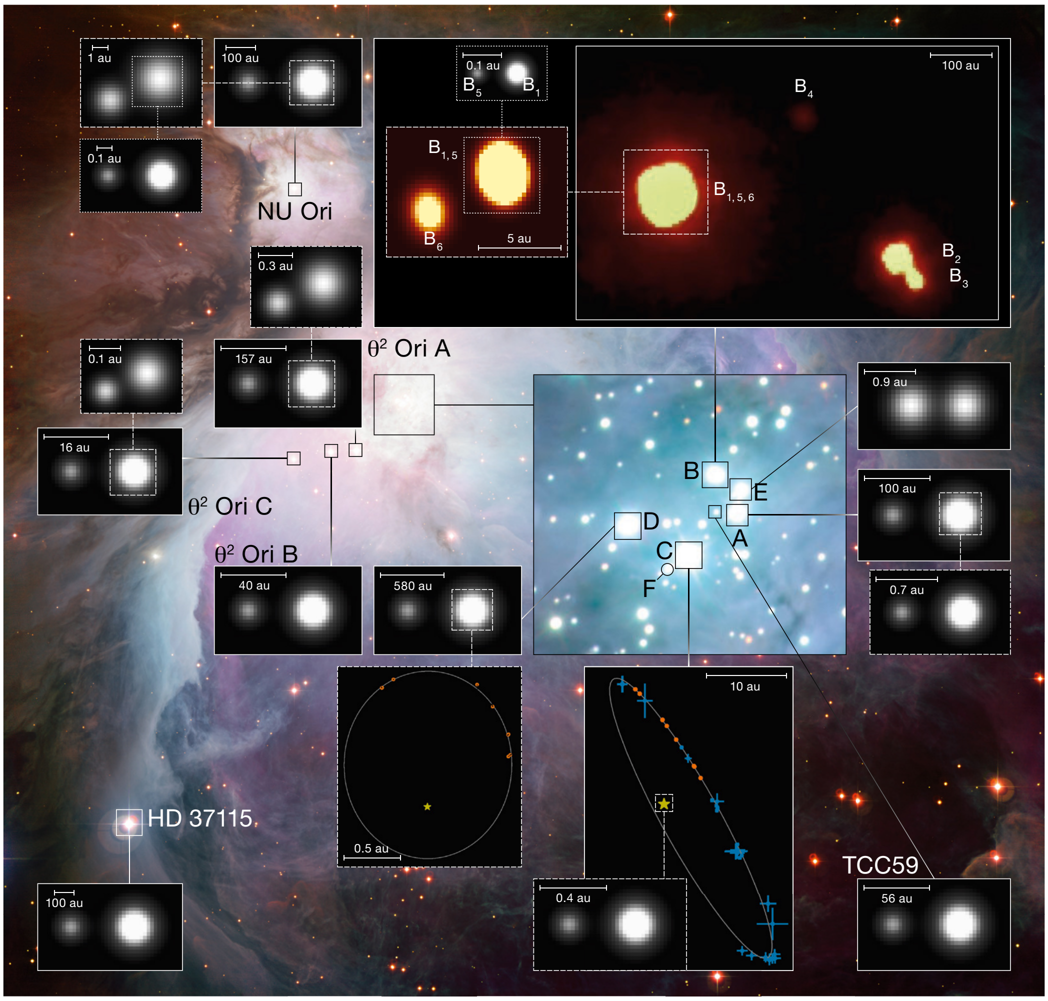

Figure 1. Overview of all observed multiple stars in the Orion Nebula. The observed 16 systems comprise a total of 22 companions. The scale of the separation of the companion is indicated in the figure. The coloured images of θ^1 Ori B are from observational data, except the greyscale B_1, B_5 system, which is only representative. The image of $B_{1,5}$ and B_6 is a reconstructed image of GRAVITY observations. The orbital positions, which are indicated for θ^1 Ori C and θ^1 Ori D, are the positions given in GRAVITY Collaboration (2018) and previous literature. The other greyscale close-up images are for illustrative purposes only. This figure is taken from GRAVITY Collaboration (2018).

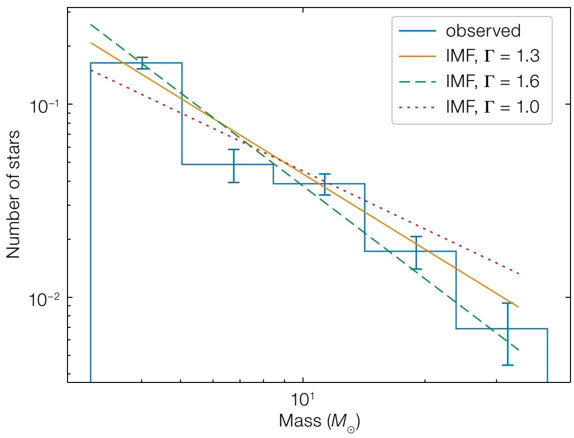

Figure 2. The observed mass distribution of the observed stars and their companions as a normalised histogram, and the initial mass functions as proposed by, for example, Kroupa (2001).

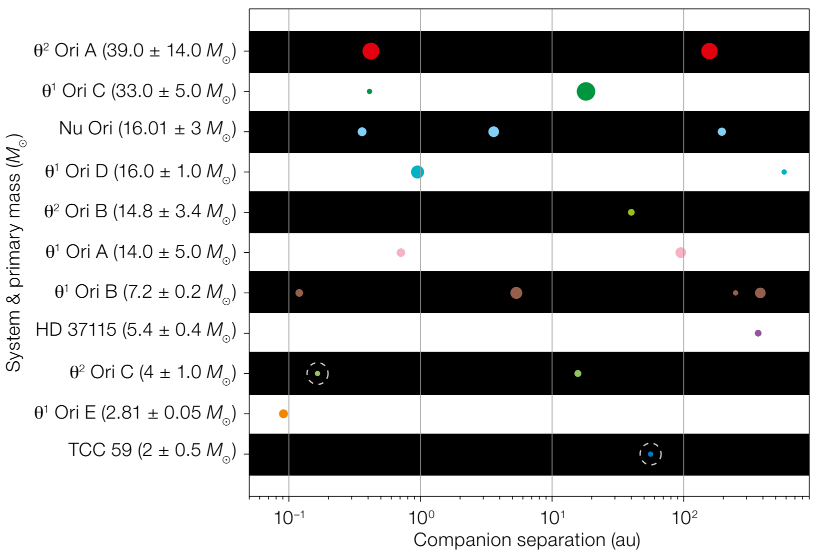

Figure 3 (below). Companion separation for all of Orion's multiple star systems, sorted by mass of the primary star. Each system is indicated by a different colour. The dot size scales with the square root of the companion mass. There are as many companions in the range 0.1–1 au as in the range 1–100 au. The dashed circles around companions of θ^2 Ori C and TCC 59 indicate missing information about the masses. (GRAVITY Collaboration, 2018) either scenario. In addition, competitive accretion predicts an anti-correlation between the mass ratio of the companion to primary star and their separation, which we do not see in our data. If stellar collisions were the dominant formation process, we would expect a strong deviation from the Salpeter IMF (Moeckel & Clarke, 2011). Thus we can exclude stellar mergers as the dominant formation mechanism for massive stars in Orion.

Summary & conclusions

We probed the Orion Nebula for massive multiple star systems with separations between 1 and 100 au. Almost all massive stars live in multiple systems. We do not see a strong preference for either core collapse or competitive accretion among the massive stars of Orion. The Salpeter IMF hints towards competitive accretion, whereas the lack of correlations between separation, system mass, primary and companion masses contradicts it. We can exclude the collision of stars as the main mechanism for the formation of high mass stars in Orion, which would result in a strong deviation from the Salpeter IMF. Our GRAVITY results highlight the crucial role of interferometry in filling the gap between 1 and 100 au, which is not accessible with traditional imaging and spectroscopic techniques.

Acknowledgements

See page 23.

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Probing the Discs of Herbig Ae/Be Stars at Terrestrial Orbits

GRAVITY Collaboration (see page 20)

More than 4000 exoplanets are known to date in systems that differ greatly from our Solar System. In particular, inner exoplanets tend to follow orbits around their parent star that are much more compact than that of Earth. These systems are also extremely diverse, covering a range of intrinsic properties. Studying the main physical processes at play in the innermost regions of the protoplanetary discs is crucial to understanding how these planets form and migrate so close to their host. With GRAVITY, we focused on the study of near-infrared emission of a sample of young intermediate-mass stars, the Herbig Ae/Be stars.

Dust in the innermost regions of the young intermediate-mass stars

The formation and evolution of protoplanetary discs are important stages in the lifetimes of stars. Terrestrial planets are born in and/or migrate into the innermost regions close to the host star. As discs evolve, different phenomena such as photoevaporation, mass-loss through winds and jets, and dynamical clearing by newly-formed planets will disperse the disc material. Thus disc evolution and planet formation are linked processes. Observing the inner regions with sufficient angular resolution is crucial for better understanding the key physical processes at play and how they combine to lead to the formation of an exoplanetary system.

Thanks to high angular resolution imaging in the optical range with the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE; Beuzit et al., 2019), and at (sub-)millimetre wavelengths with the Atacama Large Millimeter/submillimeter Array (ALMA partnership et al., 2015), rings, gaps, spiral arms, warps, and shadows have been revealed in the outer disc on scales ranging from a few tens to a few hundreds of astronomical units (au). GRAVITY uniquely probes the innermost few au where hot gas might accrete onto the star through magnetospheric accretion or be launched through winds and jets, where dust is thermally processed, sublimated, and from where it can be redistributed into the outer disc. Identifying dust traps and other planetary signposts such as dynamical perturbations in the disc is an important goal if we are to constrain inner planet formation mechanisms.

The diverse nature of the inner discs

In this contribution, we highlight GRAVITY observations that reveal the morphology of the inner dusty discs. The near infrared emission detected with GRAVITY[1] and the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER[2]; Le Bouquin et al., 2011) arises mostly in the dust sublimation front of the inner part of the protoplanetary disc. We observe wedge-shaped rims, with a smooth radial distribution of dust that is much wider than would be expected for a single dust component (GRAVITY Collaboration et al., 2019). We suggest that these inner-