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.

References

Bate, M. R., Bonnell, I. A. & Bromm, V. 2002, MNRAS, 336, 705
Bonnell, I. A. & Bate, M. R. 2005, MNRAS, 362, 915
Clarke, C. J. 2001, *The Formation of Binary Stars*, IAU Symposium, 200, 346
Close, L. M. et al. 2013, ApJ, 774, 13
Duchêne, G. & Kraus, A. 2013, ARA&A, 51, 269
GRAVITY Collaboration 2017, A&A, 602, A94
GRAVITY Collaboration 2018, A&A, 620, A116
Grellmann, R. et al. 2013, A&A, 550, 531
Kroupa, P. 2001, MNRAS, 322, 231
Moeckel, N. & Clarke, C. J. 2011, MNRAS, 410, 2799
Reid, M. J. et al. 2014, ApJ, 783, 130
Salpeter, E. E. 1955, ApJ, 121, 161
Tan, J. C. et al. 2014, *Protostars and Planets VI*, ed. Beuther, H. et al., (Tucson: Univ. of Arizona), 149

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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-

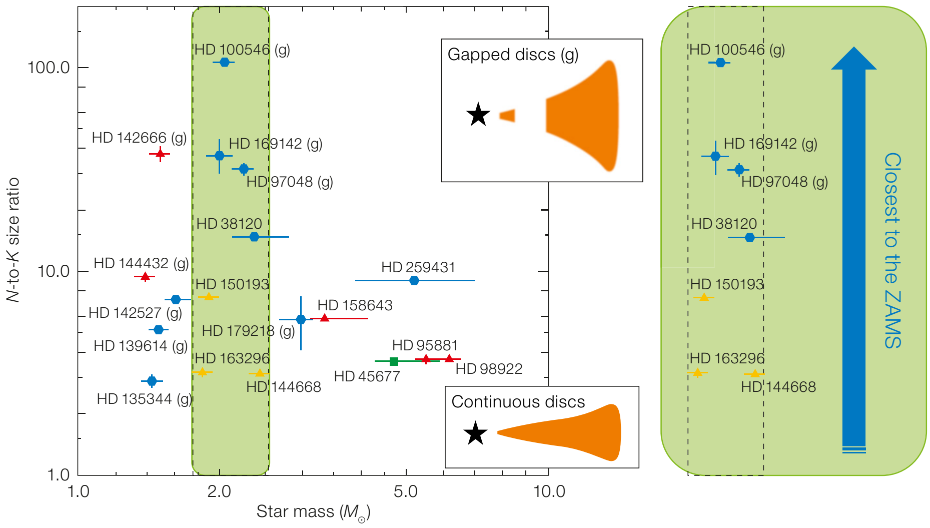

Figure 1. *N*-to-*K* size ratio of the discs as a function of the mass of the central stars. The blue diamonds denote flared/gapped discs (as sketched in the top inset), while the red triangles denote flat/continuous discs (as sketched in the bottom inset) according to the Meeus (2001) classification. The square symbol denotes an unclassified star. The gapped sources are identified as (g). The green area spots the 2 $M_\odot$ objects and the arrow indicates the position with respect to the Zero-Age Main Sequence (ZAMS).

most regions host grains of different sizes and/or compositions so that some can survive near the inner rim while others are further away. Moreover, GRAVITY reveals a slight asymmetry in most of these discs that could be explained by inclination effects for more than half the objects, while an intrinsic asymmetry should be invoked for others. From the observations of 27 targets, we confirm the size-luminosity relationship. For the luminous stars (around $10^3\ L_\odot$), a large scatter around the mean relation is observed, pointing towards a range of compositions of the inner dusty discs.

Flat, flared, gapped and continuous discs

To trace the disc regions beyond the dust sublimation rim, mid-infrared interferometry is a powerful tool, as it probes dust at temperatures down to ~ 300 K. After the MID-infrared Interferometric instrument (MIDI), the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE[3]) can now investigate disc flaring at tens of au and can help to question disc classifications based on Spectral Energy Distributions (SEDs; Meeus et al, 2001); i.e., sources with decreasing mid-infrared SEDs exhibit a flat geometry while those with flat or rising mid-infrared SEDs have flared discs. For these latter SED shapes, Maaskant et al. (2013) proposed that they could indicate a gapped disc structure.

We compare the disc sizes in the *N*-band, derived from MIDI (Menu et al., 2015), with our *K*-band measurements. To first order, the *K*-band and *N*-band sizes increase proportionally. Using the *N*- to *K*-band size ratios as a proxy, we look for general trends for about 20 objects in our GRAVITY sample; gapped sources exhibit a large *N*-to-*K*-band size ratio, and large ratios are only observed in the low-luminosity, less massive members of our sample that are older than 1 Myr.

Evolution of the inner structure

An underlying question related to disc classification is whether the sources with flared/gapped and flat/continuous discs form an evolutionary sequence. Dullemond and Dominik (2004) proposed that discs might start out with a flared shape, then become flat when going through the process of grain growth. On the other hand, Maaskant et al. (2013) proposed that both can evolve from the primordial flared discs. More recently, Menu et al. (2015) suggested that either each group could follow a distinct evolutionary path from continuous to gapped disc, or flat gapped discs could later evolve into flared discs with larger gaps.

We use the masses and ages provided by ESA Gaia observations (Vioque et al., 2018) and focus on the relative ages of objects with similar masses to avoid well-known mass bias effects for the age estimation of the young stellar objects. For 2 $M_\odot$ objects, we observe a transition from flat/continuous to flared/gapped shapes, and an increase of the *N*-to-*K*-band size ratio when the relative age increases (Figure 1). However, owing to the limited size of our GRAVITY sample, we cannot establish any clear universal evolution mechanism across the Herbig

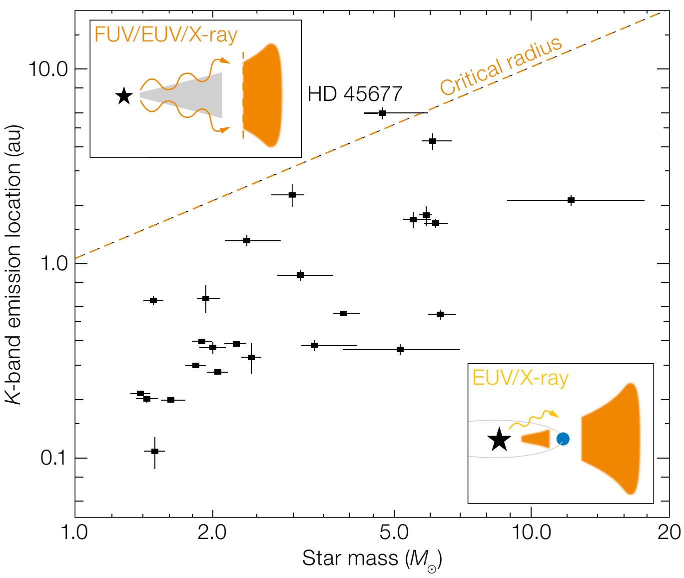

Figure 2. *K*-band emission location as measured by GRAVITY as a function of star mass. The dashed red line corresponds to the critical radius where the gap is expected to form as a result of EUV/FUV/X-ray heating from the central star. This photoevaporation phenomenon leads to a fast depletion of the inner disc and a void central cavity (as sketched in the top inset) while young planets and EUV/X-ray photoevaporation will open gaps and not deplete the inner disc quickly (bottom inset).

Ae/Be mass range and need additional observations.

Gap formation scenarios

Gaps in protoplanetary discs can be found in concentric arrangements from the inner regions out to large distances — as nicely evidenced by ALMA images (Zhang et al., 2018). Clearing by dynamical effects due to newly-born planets and photoevaporation by extreme- and far-ultraviolet (EUV/FUV) and X-ray radiation from the central star are key processes of disc dispersal through gap and inner cavity formation. In the photoevaporation scenario, gap formation takes a few 10^6 years and inner disc depletion takes about 10^5 years (Gorti et al., 2009). Since almost all the *K*-band emission we measured with GRAVITY is located at positions smaller than the critical radius where the gap is expected to form as a result of to extreme-/far-ultraviolet/X-ray heating, the discs in our sample might be shaped by forming young planets rather than by depletion resulting from photoevaporation (Figure 2).

With PIONIER, GRAVITY and MATISSE, the VLTI is perfectly equipped to reveal the gas and dust distributions in protoplanetary discs at unprecedented angular and spectral resolution.

References

ALMA Partnership et al. 2015, ApJ, 808, L1
Beuzit, J.-L. et al. 2019, A&A, 631, A155
Gorti, U. et al. 2009, ApJ, 705, 1237
Dullemond, C. & Dominik, C. 2004, A&A, 421, 1075
GRAVITY Collaboration et al. 2019, A&A, 632, A53
Le Bouquin, J.-B. et al. 2011, A&A, 935, A67
Lopez, B. et al. 2018, SPIE, 10701, 107010Z
Maaskant, K. M. et al. 2013, A&A, 555, A64
Meeus, G. et al. 2001, A&A, 365, 476
Menu, J. et al. 2015, A&A, 581, A107
Vioque, M. et al. 2018, A&A, 620, A128
Zhang, S. et al. 2018, ApJ, 869, L47

Notes

[1] GRAVITY operates in the near-infrared *K*-band, i.e., with wavelengths between 2 and 2.5 μm.
[2] PIONIER at the VLTI operates in the near-infrared *H*-band, i.e., with wavelengths between 1.5 and 1.8 μm.
[3] MATISSE at the VLTI operates in the mid-infrared *L*-, *M*-, and *N*-bands, i.e., with wavelengths between 3 and 13 μm (Lopez et al., 2018).

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Spatially Resolving the Inner Gaseous Disc of the Herbig Star 51 Oph through its CO Ro-vibration Emission

GRAVITY Collaboration (see page 20)

Near-infrared interferometry gives us the opportunity to spatially resolve the circumstellar environment of young stars at sub-astronomical-unit (au) scales, which a standalone telescope could not reach. In particular, the sensitivity of GRAVITY on the VLTI allows us to spatially resolve the CO overtone emission at 2.3 microns. In this article, we present a new method of using the model of the CO spectrum to reconstruct the differential phase signal and extract the geometry and size of the emitting region.

Protoplanetary discs at high angular resolution

Circumstellar discs are crucial to understanding how stars and planets form. They contain both gas and dust and, although there are many studies of the outer part of the disc, there are very few on the inner disc, in particular the inner gaseous disc. This hinders our understanding of the physical processes taking place in this inner part of the disc. In addition to the study of the size and shape of the continuum emission originating in protoplanetary discs around young stellar objects (YSOs), GRAVITY's spectral resolution of up to $R = 4000$ facilitates studies of the gaseous component of circumstellar material. The two most prominent components are hydrogen, in the form of the Brackett γ and higher levels of the Pfund recombination lines, and molecular gas as traced by CO ro-vibrational transitions. A direct tracer of the gas in the disc is the CO molecule. The CO emission is present at different scales throughout the disc: from the outer, cooler regions detected at millimetre wavelengths to the inner, warmer regions detected at near-infrared wavelengths. In particular, the CO ro-vibrational emission at 2.3 microns is a good tracer of the hot inner gaseous disc. Therefore, spatially resolved observations of the CO ro-vibrational transitions are crucial to constraining the dynamics and chemical composition of the inner dust-free disc.

The source

51 Oph is a fast-rotating star ($v \sin i$ = 267 km s^{-1}; Dunkin, Barlow & Ryan, 1997) and is located at a distance of 123 parsecs (Lindergren et al., 2016; GAIA Collaboration et al., 2018). Its spectrum is full of atomic and molecular lines and it is one of the very few Herbig Ae/Be stars that shows bright 2.3-micron CO overtone emission, making it an ideal candidate for near-infrared interferometric studies (Thi et al., 2005; Berthoud et al., 2007; Tatulli et al., 2008).

The CO spectrum of the star has been extensively studied spectroscopically