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THE STAR-DISK INTERACTION REGIONS OF YOUNG STELLAR OBJECTS AS PROBED WITH GRAVITY AT THE VLTI

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Abstract. Constraining the physical processes occurring in the inner region of protoplanetary disks is essential for understanding the environmental conditions of planet formation and evolution. Thanks to its unique sensitivity and angular resolution in the near infrared, the VLTI/GRAVITY interferometer has made it possible to study the inner regions (0.1-5 astronomical units) of protoplanetary disks in a homogeneous sample of nearly a hundred young stellar objects over a wide range of fundamental parameters, including T Tauri stars, Herbig AeBe stars, and a few much more massive objects. In this review, we will illustrate how this survey, combined with detailed physical modelling of certain important processes, has made significant contributions to our understanding of the physics of the inner edge of the disk (gap formation, detection of small-scale structures, misalignment of inner and outer disks) and on hot gas-emitting regions, particularly Hydrogen (magnetospheric accretion flows, wind detection). Then we will show the opportunities offered by the GRAVITY+ instrumental upgrade currently being installed at the VLTI and the synergies with other instruments.

Keywords: star-disk interaction, protoplanetary disk, optical long-baseline interferometry

1 Introduction

Various observation techniques (notably radial velocity, transit monitoring, and direct imaging) have so far enabled the detection of more than 5,700 exoplanet candidates. The demographics of detected exoplanets shows a great diversity not only in terms of architecture (number of exoplanets per star and orbits of different exoplanets) but also in terms of the properties of these exoplanets (mass, radius, separation from the host star). When all the detections from the various surveys are combined, a particular scenario emerges as the most common exo-planetary systems are super-Earth and mini-Neptune planets with masses of a few Earth mass, none of which exist in our own Solar System. On top of that, a large number of these small planets orbit their central star within the Earth's orbit (1 astronomical unit, 1 au) or even within the Mercury's orbit, which is again very different from our Solar System (Fig. 1).

Understanding the origin of such diversity in exoplanetary systems and the initial conditions that favor the formation of these compact super-Earths and mini-Neptunes requires scrutinizing the cradle of these systems, the so-called protoplanetary disks. The circumstellar disks around forming stars are mainly composed of gas with a small fraction of dust. They are reservoirs of material that can be accreted onto the star and/or sedimented and aggregated to form planetesimals. At large scales (up to a few 100s au), both ALMA at the (sub-)millimetric wavelengths and SPHERE in the optical and near-infrared ranges have been transformational in shedding new light in the complex structures of these protoplanetary disks. Their galleries of images reveal disks with a suite of bright radial rings and dark gaps, disks with arcs and spirals in dust distribution, and disks with narrow or

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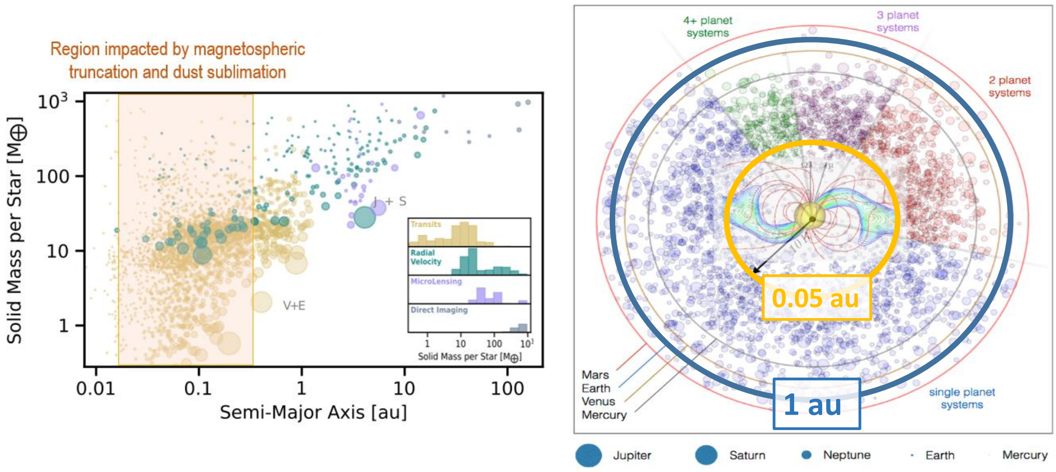

Fig. 1. Left: Distribution of exoplanets around Sun-like stars showing the predominance of small super-Earth and mini-Neptune planets peaking in the 0.01-1 au range. Adapted from Drażkowska et al. (2023). **Right:** The so-called "Kepler population" revealed by the Kepler mission. Each exo-system is located at a radial distance from its host star in a log scale, and the Earth's orbit is marked with the dark blue circle. The symbol's color codes the number of planets in the exo-system, and its size codes the size of the exoplanet. In the center, a scheme of the magnetospheric accretion region is superimposed to serve as a scale reference for a fraction of au. Adapted from Batygin & Laughlin (2015) and Blinova et al. (2016)

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wide shadows. At the same time, the gas kinematic appears also quite complex at these large scales, with maps that also exhibit (variable) features, pointing toward a highly dynamic environment. While all these features might be signposts of planets, a comprehensive view of the outcome of planet formation requests to zoom in on the innermost regions (at 1 au or less), where material is accreted onto the central star from the inner disk edge truncated by the stellar magnetic field, and where dust is sublimated by the stellar irradiation and can be trapped near this truncation radius and grow to pebbles. These interconnected processes of accretion and dust sublimation define the initial conditions of the formation and evolution of compact protoplanetary systems (Cevallos Soto & Zhu 2025; Sun et al. 2025). GRAVITY, operating in the near-infrared K-band at the VLTI (ESO), offers the sensitivity and the spatial resolution - down to sub-au scales - needed to probe the star-disk interaction regions of these disks in unprecedented detail.

2 The GRAVITY YSO Large Program view of inner dusty disks

The large survey dedicated to young stellar objects (YSO) was carried out using the guaranteed time of observation (GTO) of the GRAVITY consortium from 2017 to 2025. It enabled the observation of around a hundred protoplanetary disks around stars of different masses. When focusing on single stars, our whole sample includes $\sim$ 50 Herbig stars (2-10 $M_\odot$), $\sim$ 40 lower-mass (1-2 $M_\odot$) T Tauri stars, and $\sim$ 10 High-Mass YSOs ($\geq$ 10 $M_\odot$). This Large Program aimed at investigating the findings of pioneering works (Millan-Gabet & Monnier 2001; Monnier 2010; Eisner et al. 2014; Kraus 2015) within a statistical approach allowed by the unmatched sensitivity and accuracy of GRAVITY in the K band.

The first objective was to spatially resolve the inner au of the dusty disk to constrain the properties of the inner rim (morphology, inclination and position angles, dust grain sizes and composition). Indeed, in the K-band range, the continuum emission is dominated by the thermal emission of the dust that sublimates when irradiated by the central star. The orientations of the inner disks can be compared to those of the outer ones to detect misalignments (Bohn et al. 2022) that are suspected to create the narrow or wide shadows observed in the SPHERE images in scattered light. Our large and homogeneous sample allows us to look for trends with the properties of the central star (notably mass, luminosity, and age), and with the disk morphology. As an illustration, comparing K-band emission sizes measured with GRAVITY for ∼90 protoplanetary disks with photo-evaporation gap opening models (Gorti et al. 2009) allows us to put constraints on the processes at play (Perraut et al. 2023).

We also seek to detect asymmetries using closure phases that can be obtained by combining the four telescopes of the VLTI in triplets. With long temporal series of observations, we are able to monitor such asymetries at a few au from the central star for a few Herbig stars that are well resolved with the angular resolution of GRAVITY. This was performed for HD 98922 whose interferometric visibilities (that trace the size of the emission) appear to be more or less stable over 6 years but whose closure phases (that trace its asymmetry) are variable on a weekly/monthly basis. The GRAVITY observations are correctly reproduced by a dusty crescent-like feature orbiting the central star with a sub-Keplerian velocity (Gravity Collaboration et al. 2024). Interestingly, when looking at the location of the Br_γ emitting region, it appears to stay in-between the dusty feature and the central star.

3 Monitoring accretion-ejection in T Tauri stars

The second objective of the Large Program was to study the hot (Hydrogen) and warm (CO) gas and the excitation mechanisms (accretion, winds, jets) from which emission lines originate. Taking advantage from the high spectral mode of GRAVITY, we can obtain spectra at a resolution of $\sim$ 4000 over the whole K band in a shot, and differential interferometric observables (visibilities and phases) across the emission lines. The line-emitting regions are thus (at least partially) spatially and spectrally resolved allowing kinematic studies to be performed.

A few tens of young, low-mass (1-2 $M_\odot$; T Tauri) stars were targeted with GRAVITY to deeply probe the accretion-ejection processes through the Hydrogen I Br_γ emission line. About ten of those exhibit detectable differential interferometric signals that allowed us to extract the size of the Br_γ emitting region, and to disentangle between the low accretors (i.e., TW Hya (Gravity Collaboration et al. 2020) and DoAr 44 (Bouvier et al. 2020)), and the stronger accretors (i.e., RU Lup (Gravity Collaboration et al. 2023) and S CrA North (GRAVITY Collaboration et al. 2024)). The emission of low accretors is well modeled by a pure magnetospheric accretion model (Tessore et al. 2023) and our measurements are in great agreement with the magnetospheric accretion scenario (Fig. 2-(a)), where the stellar magnetic field truncates the inner disk and funnels the material to accrete onto the central star along the magnetic field lines (Bouvier et al. 2007; Hartmann et al. 2016). By contrast, for stronger accretors a wind contribution has to be added so as to correctly reproduce a Br_γ emitting region that is larger than the magnetospheric truncation radius, notably in the wings of the emission line (Wojtczak et al. (2024); Fig. 2-(b)).

Even more interesting, the increase in the sensitivity and accuracy of GRAVITY makes monitoring of accretion-ejection processes possible. As an example, for the North component of the T Tauri twin system S CrA, we can extract from the GRAVITY measurements the on-sky photocenters across a few spectral channels of the Br_γ emission for the two consecutive nights (Fig. 3-(a)). These on-sky displacements are derived with an accuracy of a few 10s of micro-arcseconds (i.e., a few thousandths of au at 140 pc) and trace a line almost perpendicular to the position angle of the dusty disk (in yellow), pointing toward a polar process responsible for the emission. These photocenters remain unchanged and do not exhibit a clear rotation from one night to another. Given the rotational period of the star of about 7 days, the accretion flow(s) are expected to rotate of about (360°/7) between the two nights. So we can rule out a dominant contribution of pure magnetospheric accretion, which is in agreement with the larger emitting region in the blue wing (Fig. 3-(b)). As the overlap with other observing techniques like spectro-polarimetry has been improved, we can combine the GRAVITY data sets with ESPaDOnS ones (Donati et al. 2006) to draw a coherent view of this object: the Hydrogen I H_α profile is variable (Fig. 3-(c)) with a large blue absorption in agreement with disk wind models as those developed by Lima et al. (2010). Such profiles are well reproduced with a strong accretion rate ($\sim 10^{-7}$ $M_\odot$/yr), and an intense ($\geq 10^{-8}$ $M_\odot$/yr), dense ($\sim 5\ 10^{-9}$ kg/m^3), and compact (outer radius of 10-20 stellar radii) wind. Finally, spectropolarimetry provides us with an asymmetric Stokes V signal in the He I λ5876Å (Fig. 3-(d)) that traces the magnetic field at the footprint of the accretion columns. All these findings combined together lead to the sketch in the center of Fig. 3.

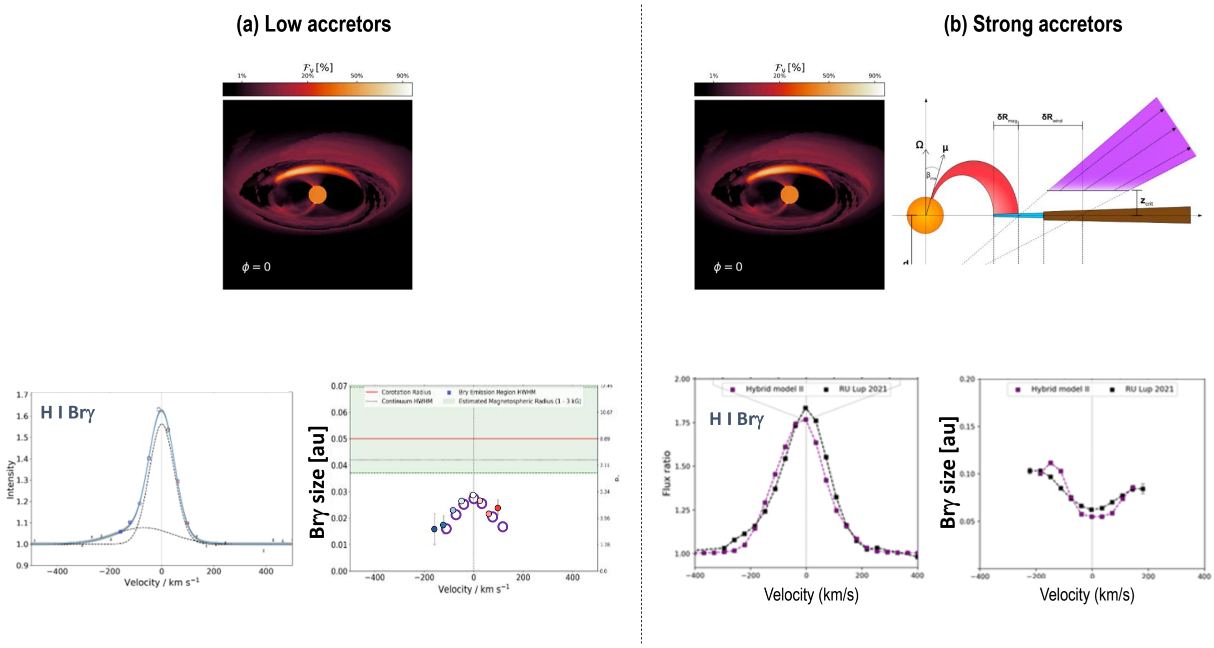

Fig. 2. Modelling the Hydrogen I Brγ emitting region of T Tauri stars through radiative transfer that produces synthetic line profiles and images (top raw), from which the interferometric observables can be derived and superimposed to the GRAVITY observations (low panels). **(a)** For low accretors, as illustrated on the TW Hya observations, a pure magnetospheric accretion radiative transfer model (open purple circles) reproduces well the size of the emitting region derived from GRAVITY measurement in each spectral channel (blue to red circles; right) of the Br$_\gamma$ line (left) that is well modelled by two Gaussian profiles. Adapted from Gravity Collaboration et al. (2020) and Tessore et al. (2023). **(b)** For strong accretors, as illustrated on the RU Lup observations, an additional contribution is needed to reproduce the Br$_\gamma$ line profile (left) and size increase in the blue wing of the line (right). On top of the pure magnetospheric accretion model, a geometrical disk wind is modelled to produce an "hybrid" model (purple symbols) that reproduces both the line profile and the size measured by GRAVITY (black symbols). Adapted from Wojtczak et al. (2024).

4 Opportunities of GRAVITY+

GRAVITY+ is a major upgrade, phased over several years, to improve the performance of both the instrument itself and the VLTI infrastructure as a whole. It began in 2019 with the replacement of the grisms, resulting in a gain of more than a factor of 2 in transmission. In 2026-2027, a new grism upgrade is planned to increase the spectral resolution to 15,000. From 2019 to 2022, a wide-field mode was implemented, allowing targets as far as 30" from the science target to be used for servoing the interferometric fringes (GRAVITY+ Collaboration et al. 2022). In 2024, a modern adaptive optics (the so-called GPAO, with new deformable mirrors and new wavefront sensors) equipped the four Unit Telescopes (UTs) of the VLTI pushing the sensitivity of the infrastructure and of GRAVITY thanks to a much better image quality at the telescope level and flux injection in the GRAVITY instrument (GRAVITY+ Collaboration 2025). The next phase is in progress with the implementation of laser guide stars (LGS) for all UTs. The latter will open a new window for the YSO studies since the LGS will be used as a guide star and targets with magnitude as low as 18 in G band (compared to 14 today) will become reachable. This is of utmost importance for the science cases dedicated to protoplanetary disks since it will allow to complete the sample by reaching the bulk of T Tauri stars that correspond to cooler, less massive, and fainter sources than what GRAVITY has already observed (Fig. 4). Redder, embedded, and younger sources like Class I will become observable with near-infrared interferometry for the first time, allowing us to test the magnetospheric accretion scenario in a different regime of accretion (e.g., higher accretion rate), and of magnetic field topology (magnetic fields are expected to be more intense and more complex). As a test case, the famous HL Tau was observed in 2024 with GPAO and the K-band continuum emission at the inner disk along with the Br$_\gamma$ emitting region were both partially resolved.

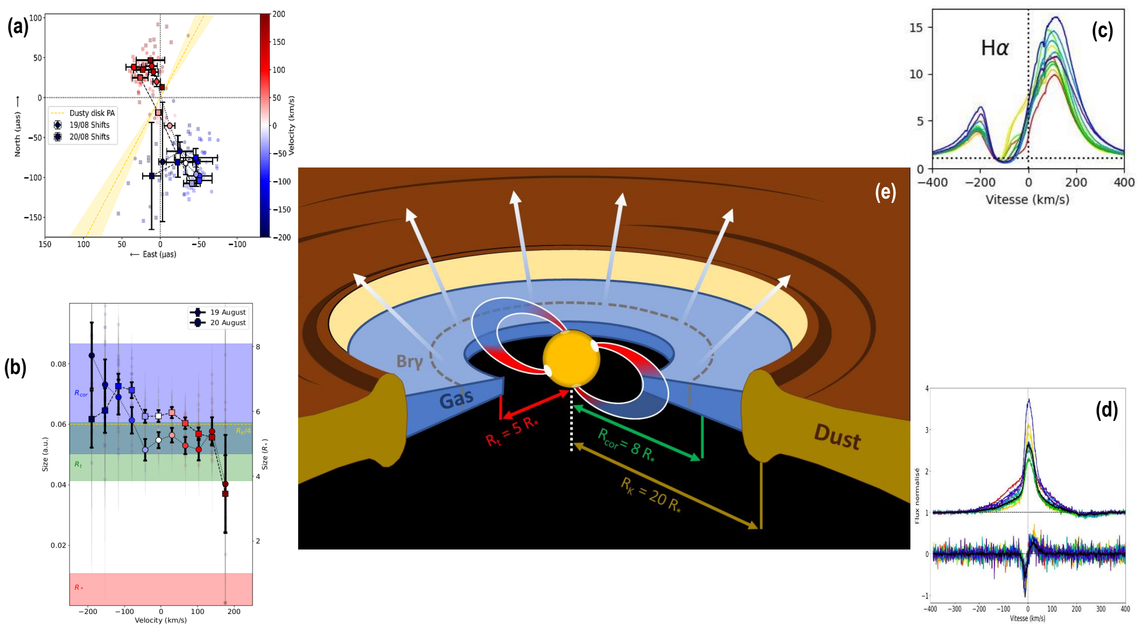

Fig. 3. Combining observing techniques to draw a coherent view of the innermost regions of the protoplanetary disk of the T Tauri star, S CrA North. **(a)** The on-sky displacements traced across the spectral channels of the Br_γ emission line with GRAVITY at a 10s μ-arcsecond scale favor a polar process for the emission. **(b)** The differential visibilities recorded with GRAVITY can be fit with a geometrical model to provide the characteristic size of the Br_γ emitting region that agrees with a combination of accretion and ejection through a wind (size's increase in the blue wing). **(c)** The H_α emission line as recorded with ESPaDOnS exhibits a deep and large absorption is its blue wing, in close agreement with a disk wind. **(d)** I (top) and clear asymmetric Stokes V (bottom) profiles across the He I λ5876Å emission line as recorded with ESPaDOnS, as a proxy of the stellar magnetic field strength and topology. Adapted from Nowacki et al. (2023) and GRAVITY Collaboration et al. (2024).

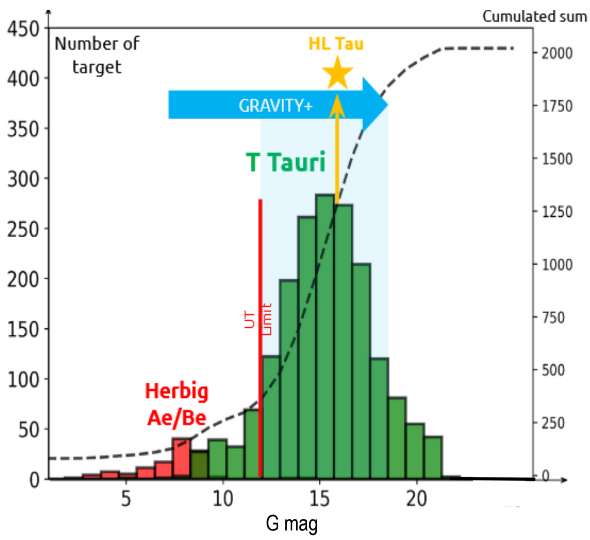

Fig. 4. Histogram of YSOs as a function of G magnitude from the catalog of Marton et al. (2023) with the Herbig Ae/Be (red bars) and the T Tauri (green bars) stars.

5 Conclusions

With its exquisite accuracy and tremendous sensitivity, GRAVITY at the VLTI has opened a fruitful avenue to scrutinize the innermost regions of the Young Stellar Objects. The GTO Large Program has already provided a consistent data set of unparalleled scope for this type of study. With its angular resolution, it allows one to probe the regions of a few tenths of au where the dust sublimation and the magnetospheric accretion occur, which corresponds to the location where the mini-Neptunes and super-Earths are observed (see Fig. 1). By giving access to fainter, more embedded, and younger objects, GRAVITY+ will allow us to extend the study to the bulk of T Tauri stars and to Class I sources as well as to monitor the accretion flows at high-cadence (1 hour or less).

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