SF2A 2023
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THE GRAVITY VIEW OF THE INNERMOST REGIONS OF PROTOPLANETARY DISKS

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Abstract. Probing the innermost regions of the protoplanetary disks where micron-sized dust grains grow to pebbles and larger bodies producing the first building blocks of planets, and investigating star-disk interactions at sub-astronomical unit (sub-au) scale are of utmost interest as they define the initial and environmental conditions for planet formation. Since its installation in 2016, VLTI/GRAVITY has brilliantly illustrated the potential of the high angular and spectral resolutions to constrain the processes at play in the central au's of protoplanetary disks in the near-infrared K-band (around 2.2 μm). With a sample of a hundred young stellar objects (YSO), from solar-like (namely the T Tauri) to high-mass YSO, the YSO GTO Large Program has gathered a large homogeneous data set allowing us to simultaneously study the emission of dust and of the hot (e.g., Brγ Hydrogen I line) and warm (e.g., CO bandheads) gas. In this talk, I will review the most striking results obtained with GRAVITY during its first 5 years of operation and illustrate the opportunities opened by the future upgrade GRAVITY+.

Keywords: Pre-main sequence stars, protoplanetary disks, optical long-baseline interferometry

1 Introduction

With more than 5300 exoplanets detected so far, it is clear that planet formation is a robust and efficient process. Statistically, most solar-mass stars should host at least one planet. The current population of known exoplanets shows an incredible diversity, both in the nature (mass, radius) of the planets themselves, but also in the architecture of these systems. More striking, the majority of exoplanetary systems revealed by Kepler transits consist of chains of low-mass planets, super-Earths and mini-Neptunes alike, located close to their host stars. The origin of this diversity, its connection to planetary migration, and whether it is inherited from the initial stages of planet formation is still unclear. These observational results question what are the initial conditions that would favour the formation of compact, short-period planetary systems in the inner disk of young stars, at distances ranging from 0.1 astronomical units (au) to a few au from the central star (e.g., Mishra et al. 2023; Batygin & Morbidelli 2023; Li et al. 2022).

Understanding the origin of such a diversity requires exploring the birth environment of these planets, namely the planet-forming protoplanetary disk, that plays a crucial role as the mass reservoir of gas and dust from which matter is accreted onto the star and from which planets are built. The accretion of disk material onto the stellar surface directly impacts the star's properties and early evolution. It also produces high-energy radiation that illuminates the circumstellar disk and the proto-atmosphere of nascent planets, thus drastically affecting their physical and chemical evolution. Star formation, planet formation, and disk evolution processes occur simultaneously and influence each other. These mutual influences last for only a few million years but they set stellar and planetary properties that persist for billions of years. Thus, a deep understanding of the structure and evolution of protoplanetary disks, on both local and global scales, is required to comprehend the diverse outcome of the planet formation process. Thanks to its deep sensitivity in the near-infrared K-band and its exquisite spatial resolution of a fraction of au, GRAVITY (GRAVITY Collaboration et al. 2017) at the combined focus of the Very Large Telescope Interferometer (VLTI) of the European Southern Observatory (ESO) allows us to probe their inner au-scales.

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2 Probing the dust distribution in the innermost regions of the protoplanetary disks

Since its start of operation in 2016, about 60 Herbig Ae-Be stars and 40 G-K-M T Tauri stars have been observed within the GRAVITY YSO Large Program, which allowed the inner disk radius - stellar luminosity relation to be explored over more than 4 decades in stellar luminosity, and to look for trends between the properties of the central star and the disk morphology. Combined with the previous PIONIER surveys (Lazareff et al. 2017; Kluska et al. 2020), our GRAVITY data sets have enabled us to constrain the geometry and the temperature of sublimation fronts (GRAVITY Collaboration et al. 2019, 2021), highlighting their widening, which could trace a highly differentiated particle size distribution. These studies provide unique inputs to test advanced simulations of the inner disk rim, notably regarding the presence of a dead-zone at the inner edge (Flock et al. 2016, 2017).

With our large sample, the origins of gaps in the innermost regions were put into test through a comparison between the dust emission sizes measured with GRAVITY and size predictions from photoevaporation models. In the model of Gorti et al. (2009), heating by the stellar radiations in the Extreme and Far UV, and the X-rays induces the opening of a gap in the protoplanetary disk with a peak efficiency at a critical radius r_c; this gap formation takes ∼4 Myr for solar-type masses and is likely shorter for masses larger than 3 $M_\odot$, while the clearing of the whole cavity takes ∼0.5 Myr. All GRAVITY measurements (but for one object) lie below the critical radius computed for a standard 10^4 K gas temperature (Fig. 1). For the younger objects of our sample (blue symbols), the smaller sizes compared to r_c are compatible with a scenario where photo-evaporation has just started and the cavity is not totally void of dust, but for the older sources (yellow, green, and red symbols), EUV/FUV/X-ray photoevaporation seems not to be the dominant process that clears the inner cavity and other scenarios might be invoked (EUV/X-ray photoevaporation, dynamical clearing by young planets, ...).

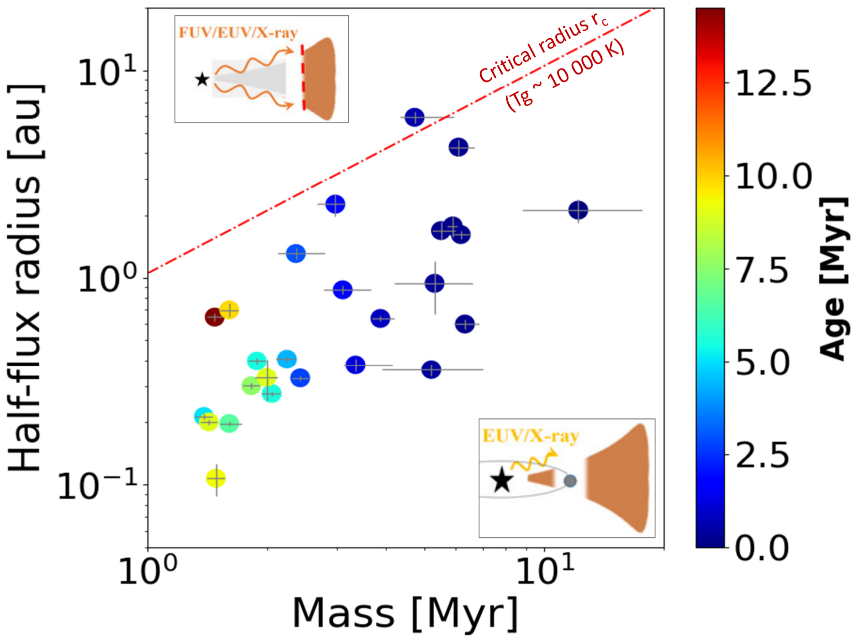

Fig. 1. K-band half-flux radii measured with GRAVITY of a function of the mass and age (color) of the Herbig stars of the GRAVITY YSO sample, compared to the critical radius (red dash-dotted line) when gaps are opened by X-EUV-FUV photoevaporation as modeled by Gorti et al. (2009). Adapted from GRAVITY Collaboration et al. (2019).

3 Probing the magnetospheric accretion flows

Thanks to its spectroscopic ability with a spectral resolution of about 4000 over the whole K band, GRAVITY has led to the spatial resolution of the Hydrogen Brγ emitting regions around a sample of Herbig and T Tauri stars. The GRAVITY measurements allow the size of the emitting region to be determined: this region is in most of the case more compact than the continuum emitting region, and corresponds to a few stellar radii. The comparison between these sizes, the corotation radius, and the truncation radius derived from spectro-polarimetric observations allows the dominant driver of the Brγ line to be investigated: if the magnetospheric accretion process dominates, the Brγ emitting region is expected to be on the order of the corotation radius, or even slightly more compact, which is what we observed for the weakest accretors in our sample DoAr 44 (Bouvier et al. 2020), TW Hya (Gravity Collaboration et al. 2020), and CI Tau (Gravity Collaboration et al. 2023a). For most of the other objects, the Brγ half flux radii extend to scales outside the corotation radius, suggesting a wind contribution (Gravity Collaboration et al. 2023b). More interestingly, the interferometric differential phases provided by GRAVITY across the Brγ line are proxies of offsets between the photocenters of the continuum and of the Brγ line emitting regions, that could be interpreted as the first resolution of an accretion flow onto the central star as in the case of DoAr 44 (Bouvier et al. 2020).

Within the framework of the ERC SPIDI project*, huge efforts were made to develop advanced Radiative Transfer codes (Tessore et al. 2021) and Magneto-HydroDynamical simulations (Pantolmos et al. 2020) to model the inner disk rim and the accretion flows onto the central star. These tools produce intensity maps from which synthetic interferometric observables could be computed and compared with our GRAVITY observations (Tessore et al. 2023).

4 Prospects for GRAVITY+

While the unique, homogeneous data set obtained with the GRAVITY instrument has already enabled us to carry out statistical studies, the current instrumental context is even more promising, particularly with the imminent arrival (2025) of the GRAVITY+ instrument at the VLTI. GRAVITY+ is an upgrade of the entire VLTI infrastructure, which will equip the 4 unit telescopes (UTs) with modern adaptive optics (new deformable mirrors, new wavefront sensors) and laser guide stars. Both instrumental improvements will have an impact on all the interferometric instruments currently in operation or planned for the future. As far as GRAVITY is concerned, they will significantly increase its sensitivity and sky coverage, by enabling telescope guidance on stars of magnitude as low as 18 in G band (compared to 14 today), and fringe tracking on sources of magnitude 13 in K band with UTs (compared with 10 at present) and possibly separated by 30" (instead of 2" at present). GRAVITY+ will enable us to spatially resolve for the first time in the near-infrared range the environment of most T Tauri stars (over 300 stars in the Taurus star-forming region alone), and thus extend our observations to several star-forming regions (Fig. 2), such as Serpens (1-3 Myr old), σ Ori (3-5 Myr old), and Upper Sco (5-10 Myr old). The future sample will thus cover a wider range of parameters in terms of mass, luminosity, age, and accretion regime.

In addition, this increase in performance will provide a better overlap with other observational techniques, particularly spectro-polarimetry. This technique, notably with the ESPaDOnS (Donati et al. 2006) and SPIRou (Donati et al. 2020) instruments at the Canada-France-Hawaii-Telescope, enables us to determine the topology of the stellar magnetic field, follow its temporal evolution, and study its impact on the inner disk. Combining these observations with the new GRAVITY+ observations will allow the magnetospheric accretion scenario to be tested for a more representative set of young stars, including lower-mass, and younger embedded sources that would become observable with near-infrared interferometry for the first time.

5 Conclusions

The GRAVITY Young Stellar Object Large Program has already provided an invaluable homogeneous data set enabling demographic studies, variability follow-up, and test of inner disk and star-disk interaction advanced models. Combined within multi-technique and multi-wavelength campaigns, and with advanced radiative transfer and MHD simulations, the GRAVITY+ observations will be key to obtain a global picture of the inner parts of the protoplanetary disks and provide clues to the conditions prevailing over the formation of close-in planets.

We acknowledge the funding of the French National Program of Stellar Physics (PNPS) and support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 742095; *SPIDI*: Star-Planets-Inner Disk-Interactions), and from LabEx OSUG@2020 (Investissements d'avenir - ANR10LABX56).

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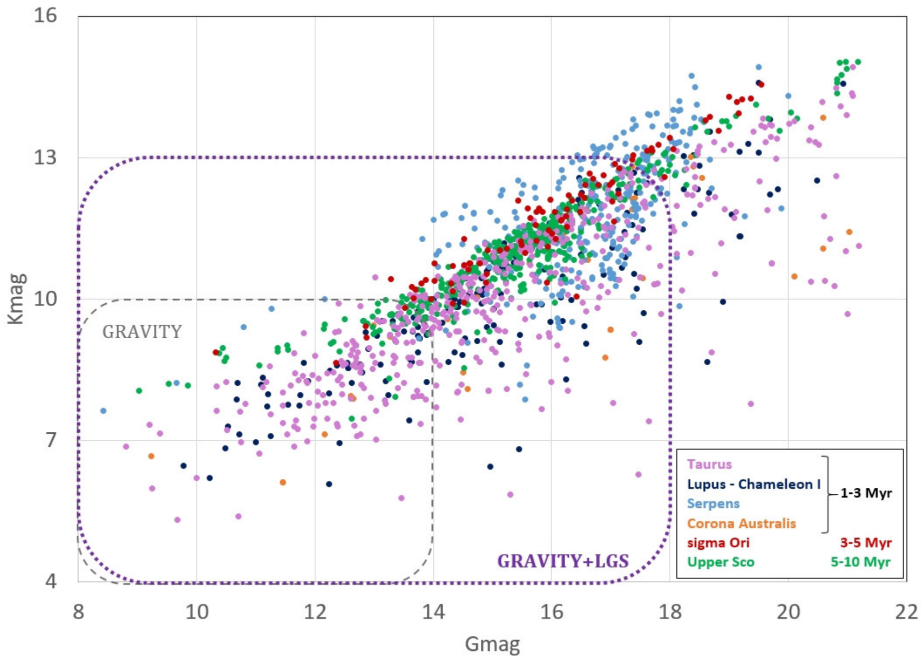

Fig. 2. Color-color diagram of the YSOs currently observable with GRAVITY (in the gray dashed area) and observable in the future with GRAVITY+ when equipped with the Laser Guide Stars (LGS; purple dotted area). The color codes the star-forming regions of different ages.

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