GIARPS/GRAVITY survey: broad-band 0.44-2.4 micron high-resolution spectra of T-Tauri and Herbig AeBe stars. Combining high spatial and high spectral resolution data to unveil the inner disc physics

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Abstract The GIARPS/GRAVITY survey aims to obtain a set of high spatial and spectral resolution data for a sample of T-Tauri and Herbig AeBe stars ($\sim$ 100 objects) from the VLTI/GRAVITY GTO sample of Young Stellar Objects (YSOs). GIARPS is a broad-band spectrometer combining HARPS-N and GIANO which allows high-resolution spectra from 0.44 μm ($R \sim 115000$) to 2.44 μm ($R \sim 50000$) in one observation. By combining this high spectral resolution with the high spatial resolution ($\sim$ 1 mas) of GRAVITY, a view of unprecedented detail can be obtained of the innermost regions of circumstellar discs in YSOs spanning a wide range of masses (0.1–5 $M_{\odot}$) and ages (10^5–10^7 yr). The ultimate goal is to model the accretion and ejection mechanisms, and study how they evolve as a function of YSO mass and age, using the spatially and spectrally resolved atomic and molecular lines from the inner gaseous regions.

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1 Circumstellar processes in young stellar objects

Disc structures are ubiquitous in astrophysics. In star formation, they are instrumental in mediating accretion of matter onto new-born stars as well as in ejecting matter through collimated outflows. A widely accepted paradigm is that stars form by gathering matter falling from the disc onto the central protostar. Unfortunately, the early phases of this process are difficult to observe, due to heavy obscuration from the parental gas/dust core and lack of spatial resolution. On the other hand, the subsequent formation stage of pre-main sequence stars (PMSs) is easier to study as the sources are less embedded. In addition, PMSs still exhibit a significant accretion rate (e. g $\sim 10^{-8}\,M_{\odot}$ yr^{-1} in Classical T-Tauri stars - CTTSs). Typically, PMSs with discs also show collimated bipolar jets, through which $\sim 10\,\%$ of infalling matter is ejected.

A shared view is that in CTTSs, i. e. low-mass ($M < 2\,M_{\odot}$) PMSs with a circumstellar disc, an intense stellar magnetosphere truncates the inner disc at a few stellar radii and the accreting gas falls onto the stars in funnels along field lines (magnetospheric accretion scenario; for details see review by [9]). However, the more massive class of PMSs, the so-called Herbig Ae/Be (HAeBes) stars ($M \sim 2-10\,M_{\odot}$) do not seem to host strong magnetic fields ([14], [2]). This suggests that the accretion scenario might change with stellar mass and, at the high-mass end of HAeBes, it might be replaced by untruncated discs impinging on the stellar surface.

Another major issue in disc evolution is how matter in the disc loses angular momentum in order to accrete onto the stellar surface. A few mechanisms have been proposed, namely Magneto Rotational Instability, Hall effect, Gravitational Instability, Disc Winds (e. g., [11], [13], [12], [10]), but none of these appears to be conclusive (e. g. [9]). Recently, [8] has proposed that the early accretion stage may leave a massive inner disc, which subsequently feeds a residual accretion due to low viscosity levels, so there is no requirement to involve matter in the whole disc as usually believed. In principle, the collimated outflow can carry angular momentum away, but the collimating driver itself is still unclear. Models include magneto-centrifugally driven winds from the accretion disc, along field lines from (i) the stellar surface, or (ii) the region of interaction between the stellar magnetic field and the disc(i.e. X-wind), or (iii) the disc surface (i.e. disc-wind). Determining the mechanism responsible requires a knowledge of size, width, and geometry of launching regions.

Both accretion and ejection occur in the innermost parts (few AU) of a circumstellar disc. As these processes are intimately linked to the global evolution of the disc, they determine the evolution of both stars and planets. The innermost few AU of circumstellar discs are thus crucial in testing the different scenarios which lead to a comprehensive physical picture of the system formation. Furthermore, it is also critical to understand how this picture changes with the stellar mass to gain a full grasp of the first stages of stellar and planetary system evolution.

2 Aims of the GIARPS/GRAVITY survey

Ideally, the following questions should be addressed via observations, to gain an in-depth view of star-disc interactions:

1. What accretion mechanisms operate in stars of different masses?
2. What are the physical conditions and accretion rates of the accreting gas streams?
3. The predictions of which models best fit spatially resolved observations of jet launching regions?

Clearly, we need to probe the physical conditions and kinematics of gas inside ~ 1 AU to deal with these issues and test the different scenarios. Thus, the relevant kinematics and physical gas components can only be disentangled using a combination of high spatial and high spectral resolution observations. The recent availability of sensitive near-infrared interferometers (GRAVITY at the VLTI) and optical/near-infrared broad-band spectrometers (GIARPS at the TNG) is opening up unprecedented high-resolution observational window, which will facilitate a major step forward in our understanding of accretion processes in YSOs.

GIARPS combines the high-spectral resolution capability of the spectrometers HARPS-N in the optical and GIANO in the near-infrared ([5]), providing high-spectral resolution ($R \sim 112000$ in the optical to $R \sim 48000$ in the near-infrared) on a band ranging from 0.44 to 2.4 μm. It has been available at the Telescopio Nazionale Galileo (Canary Islands) since 2016. It will be able to kinematically disentangle the various gas components from the stellar photosphere (HARPS-N) to the inner disc (GIANO) and, thanks to the large number of lines *simultaneously* detected, to trace the physical conditions in the emitting gas (Brackett and Paschen HI, and HeI lines, CO overtone bands). Unfortunately, a few critical parameters, such as inner dusty disc size and inclination, as well as size of the line emitting regions, would remain degenerate and can only be determined by high-spatial resolution observations.

However, even for the nearest young stars (~ 150 pc), 1 AU translates into ~ 7 mas. Currently, such high spatial resolution can only be obtained with optical/IR interferometry at the ESO/VLTI, where the latest generation beam combiner GRAVITY ([7]) allows a major improvement in sensitivity and achieves an angular resolution of $\sim$1 mas. On the other hand, GRAVITY can only operate in low and medium spectral resolution (up to $R \sim 4000$) in the K band (1.95–2.5 μm). Furthermore, GRAVITY can only either provide a snapshot view of a system with a limited number of baselines, or produce an image of the stellar system by collecting observations over a larger range of baselines which may take days or months. Therefore, target variability may bias the interferometric information. Meanwhile, GIARPS can complement the GRAVITY spectral data, helping to remove the degeneracy,

So, the high-spatial and spectral resolutions achieved by the two instruments are complementary.

Spectral variability is one further powerful tool that allows access to the 3D structure of the inner disc and the circumstellar environment, to better understand the accretion/ejection processes. PMSs of all masses exhibit accretion variability on all timescales, from days to years ([9], [1]). Periodic variations of spectrally resolved line profiles have been successfully used to infer the spatial distribution of accreting gas around T-Tauri stars ([3]). Variations related to the morphology of the accreting gas are expected to be correlated with the stellar rotation period (few weeks), whereas variations on longer scales (months, years) are related to larger-scale events, e. g. gravitational instabilities in the disc or interactions with closer companions (see e. g. [4]).

3 Programme status

The GIARPS/GRAVITY survey takes advantage of GTO time with GRAVITY (PI: R. Garcia Lopez) already allocated to a consortium of European Institutes for high-spatial resolution observations of young stellar objects. The consortium has been awarded 20 nights on the UT and 120 nights on the AT telescopes at the VLTI. The programme is in progress and aims to observe a sample of more than 100 YSOs of different mass, age, and accretion rate. The first results are discussed in [6].

A collaboration between the GRAVITY GTO programme and a team of Italian astronomers stemmed from the availability of GIARPS at Italy's Telescopio Nazionale Galileo. The GIARPS/GRAVITY survey will yield high-resolution spectra of both T-Tauri stars and HAeBes from the list of GRAVITY targets. A pilot programme (PI: F. Massi) of 3 nights was carried out in December 2017, during the Italian semester AOT37, and a first sample of 17 targets were observed. Another 7 nights have already been allocated in two semesters (20018B and 2019A) of international CCI-ITP time (PI: A. Caratti o Garatti). Finally, 8 hours have been allocated to a pilot programme for studying spectral variability of PMSs (PI: F. Massi) in the Italian semester AOT38 (December 2018).

Figure 1 shows a sample of GIARPS spectra, still uncalibrated, from four Herbig Be stars (spectral type from B0 to B9) obtained during run AOT37. The optical band displays photospheric hydrogen absorption lines (Balmer series) in two cases (GU CMa and HD37806), some lines partially filled with emission. The other two stars (MWC 137 and Z CMa) exhibit Balmer lines in emission. Due to the low S/N, these spectra will be resampled to a lower spectral resolution. Hydrogen Hα is also shown, always in emission. As for the near-infrared band, Fig. 1 shows hydrogen Paβ, Paγ, and Br16 lines. All these lines are in emission. Interestingly, the Paschen and Brackett profiles for MWC 137 and GU CMa are clearly double-peaked, a signature of a circumstellar disc.

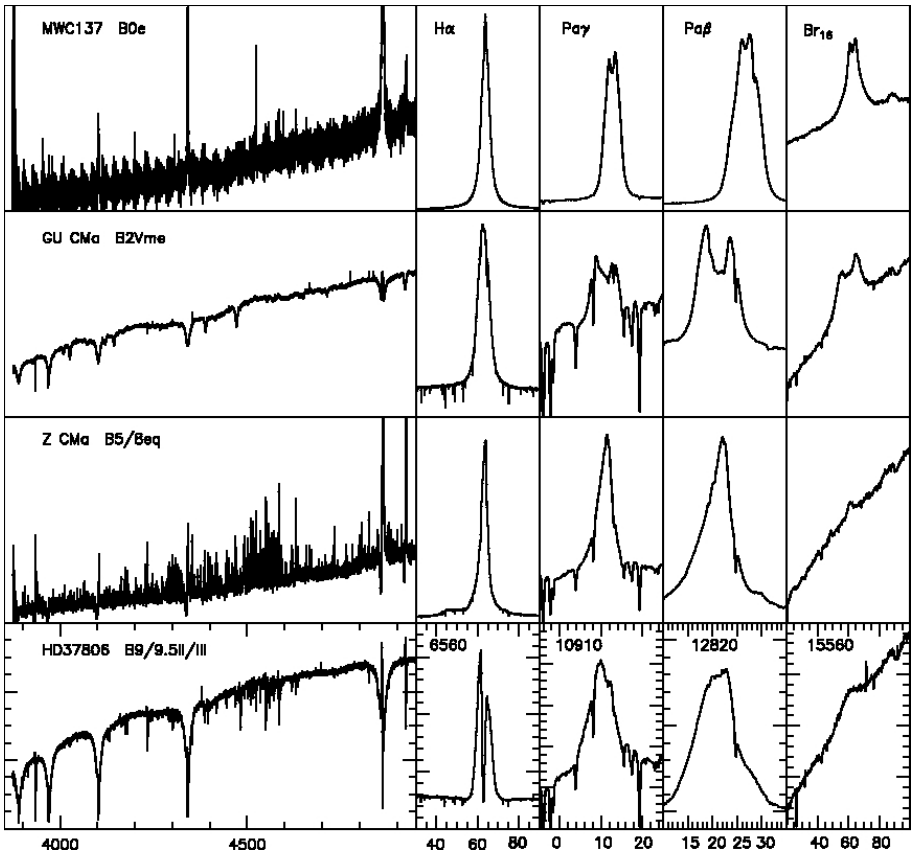

Fig. 1 GIARPS uncalibrated spectra for four Be stars, from top to bottom: MWC 137, GU CMa, Z CMa, and HD37806. The boxes display, from the left: a fraction of the optical band (wavelengths in Å on the bottom axis), and the optical/near-infrared hydrogen lines Hα, Paγ, Paβ, and Br16. Central wavelength, in Å, are indicated on the top left corner of the boxes in the bottom row. The velocity intervals of the near-infrared spectra are: 2700 km s^{-1} (Hα), 800 km s^{-1} (Paγ), 470 km s^{-1} (Paβ), and 1500 km s^{-1} (Br16).

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