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A. Siebert, K. Baillié, M. Béthermin, F. Cantalloube, E. Josselin, N. Lagarde, J. Malzac, J. Richard, L. Selliez, O. Venot (eds)

GRAVITY+: A NEW EYE ON YOUNG GIANT EXOPLANETS

N. Pourré[1], The ExoGRAVITY collaboration and The GRAVITY+ collaboration

Abstract. The instrument GRAVITY on the Very Large Telescope Interferometer is already identified as a powerful exoplanet imager due to its high-astrometric precision, its medium spectral resolution in the near-infrared, and its ability to spot exoplanets at short separation ($<$ 100 mas) from their star. Since summer 2024, the upgrade GRAVITY+ has brought the instrument capabilities even further thanks to state-of-the-art adaptive optics on the four 8-meter telescopes. The sensitivity and contrast that are now routinely achieved will enable finer spectral characterization and detection of lower mass exoplanets on closer orbits. It makes GRAVITY+ a highly promising instrument for confirming and characterizing exoplanets that will be revealed by the space telescope Gaia in 2026.

Keywords: exoplanet, direct imaging, optical interferometry

1 Introduction

Detection, astrometry and spectra The four 8-meter diameter Unit Telescopes (UT) of the Very Large Telescope Interferometer (VLTI) form baselines of maximum 130 meters. This is why GRAVITY provides exoplanets astrometry more than an order of magnitude more precise than single telescopes. However, at separation closest to these 60 mas, the star flux injected in the GRAVITY science fibers is too strong, and planet signal is lost in noises induced by star flux (photon noise, systematic noise sources, coherent noise, Pourré et al. 2024). Still, the interferometric nature of the observation induces a diversity that is more than welcome for disentangling the exoplanet light from the starlight. Thanks to a dedicated data reduction strategy using this interferometric diversity, GRAVITY was able to observe exoplanets down to 95 mas separations (Lacour et al. 2021), further in than any other single telescope instrument so far. Moreover, GRAVITY is not only able to detect challenging planets, it also provides exoplanet spectra from 2.0 μm to 2.4 μm at resolution of 500 (MEDIUM resolution mode) or 4000 (HIGH resolution mode). This makes GRAVITY a tool of choice for atmospheric characterization of directly imaged young giant exoplanets.

Limited field of view The major limitation of GRAVITY (and GRAVITY+) is the limited field of view of the instrument. The companion position must be known by around 60 mas on UTs for its light to enter the single mode fiber. Therefore, it is necessary to pave the field with different pointing in order to reveal a companion with poorly known position. Albeit being intensive in telescope time, this method proved successful for bringing first direct detections (e.g. Hinkley et al. 2023). But more generally, GRAVITY observation focused on exoplanets whose positions are already constrained by classical direct imaging or indirect astrometry.

Results The astrometric and spectrometric capabilities of GRAVITY have been used extensively to characterize massive exoplanets and brown dwarf companions, using their orbit (ex: Lacour et al. 2021), bolometric luminosity (ex: Nowak et al. 2020) and near-infrared spectrum (ex: Balmer et al. 2025). Wrap-up papers are currently in preparation for consistent re-analysis of exoplanets and brown dwarf observations realized by the ExoGRAVITY consortium (for luminosities and spectra Kammerer et al. submitted, for orbits Roberts et al. in prep). The successes of GRAVITY in the exoplanet field, and in many other science cases (galactic center, young stellar objects, active galactic nuclei,...), have motivated a major update of the instrument and of the whole VLTI. The ongoing GRAVITY+ upgrade has already delivered the most crucial aspect for exoplanet

[1] Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

science: the new, state-of-the-art adaptive optics. These were installed at the end of 2024.

In section 2, we will describe the improvement we can deduce from the first observations with GRAVITY+. Then, in section 3 we will detail the future for exoplanets with GRAVITY+, both the current instrumental developments and the characterization of candidates detected by astrometry in the Gaia data release 4.

2 The GRAVITY+ upgrade

2.1 Nature of the upgrade

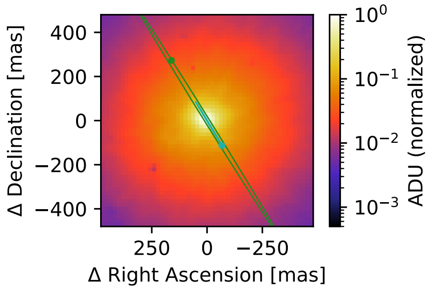
GRAVITY+ includes many aspects (Gravity+ Collaboration et al. 2022). For direct exoplanet observations, the most critical element is the replacement of the 20 years old adaptive optics of the UTs (MACAO, Arsenault et al. 2003) by state-of-the-art extreme adaptive optics, called GPAO (first light paper, GRAVITY+ Collaboration 2025). As a result, the Strehl ratio increases from 40% to 80% and the signal-to-noise ratio of direct exoplanet imaging is improved in two ways: the leaking of the starlight at the exoplanet position is greatly reduced (less noise), and the flux of the exoplanet itself is better coupled to the fiber (more signal). The four GPAO systems are offered to the community since end-2024.

The GRAVITY+ upgrade also includes the commissioning of laser guide stars for each of the UTs. Even if the main purpose of the laser guide stars is to extend sky coverage for extragalactic targets, it will also enable observation of exoplanets orbiting young embedded stars that are too faint for the natural guide star mode of GPAO. The laser guide stars will be available end-2025.

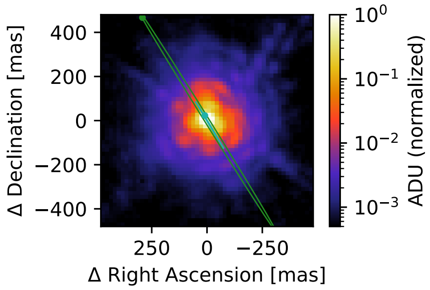
2.2 Some first light results

As soon as the GPAOs were on-sky, it was clear that it would provide exoplanet observations of drastically improved quality compared to the old MACAO. Figure 1 shows point-spread functions for a bright star (β Pictoris) in H-band. From these acquisition camera images, it is clear that the smearing of star-light is greatly reduced at the planets' positions. This diminution of stellar noise improves both the detectability of companions and the contrast spectra of the exoplanets observed.

The improvement on contrast spectra is shown on Figure 2 for two regimes: HR 8799 e, a rather faint exoplanet (K$\sim$16) in MEDIUM resolution, and β Pictoris b, a bright exoplanet (K$\sim$12) in HIGH resolution mode. For similar atmospheric conditions and integration time, the improvement in signal-to-noise ratio is of the order of a factor 10. In the faint regime, it will help for the detection of cooler and less massive exoplanets and brown dwarfs. During commissioning, we already detected a cool brown-dwarf, HD 4113 C, at an apparent magnitude around K=21 (GRAVITY+ Collaboration 2025). For brighter targets, like β Pictoris b, the higher signal-to-noise ratio enables a finer characterization of the exoplanet atmosphere. We can now identify less abundant species, such as isotopes, which can be additional tracers of exoplanet formation (Zhang et al. 2021). Also, thanks to the high quality of observations, we can now consider investigating temporal variability in spectra, that can be related to variations in the exoplanet cloud coverage.

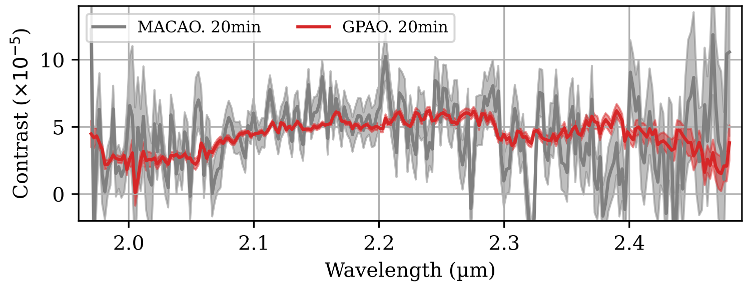


(a) Old adaptive optics: 2020-02-12

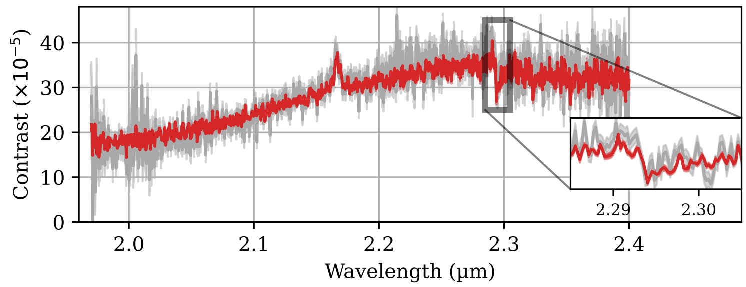


(b) New adaptive optics: 2024-12-20

Fig. 1: Comparison of images of β Pictoris with the old adaptive optics MACAO (**Left**) and with the new adaptive optics of GRAVITY+, GPAO (**Right**). Images averaged over 30s, at H-band ($\lambda \sim 1.6$ μm) from the acquisition camera of the instrument. Projected orbits of β Pictoris b and c, and position at the time of the observations, in green and cyan, respectively.



(a) HR 8799 e contrast spectrum in MEDIUM resolution ($R \sim 500$)



(b) β Pictoris b contrast spectrum in HIGH resolution ($R \sim 4000$)

Fig. 2: Comparison of observed contrast spectra of HR 8799 e (**Up**) and β Pictoris b (**Down**) with the old adaptive optics MACAO and with GPAO. All spectra are extracted from 20 min integration on the exoplanets, in comparable good atmosphere quality (Seeing $\sim$ 0.6 arcsec, $\tau_0 \sim$ 6 ms)

3 In months/years to come

3.1 Instrumental developments

The new GPAOs bring the UTs close to their diffraction limit in the near-infrared. It means that aberration residuals are not anymore dominated by atmosphere residuals, but tend to be dominated by static or quasi-static effect (aperture diffraction, NCPA, low-wind effect). Also, the new adaptive optics use Shack-Hartmann wavefront sensors that have a wide linearity range, and thus are especially convenient for injection of low order modal offsets.

NCPA control for VLTI At VLTI, the NCPA control is a top-priority because of the long optical path (50 to 200 m) and the many optics between the GPAOs and the instruments. We use a Zernike harmonic modulation method to measure the NCPA from focal plane images at the VLTI lab (Pourré 2024). Recent measurements have shown that the NCPA can amount up to 250 nm rms (mainly defocus) between GPAO and the IRIS camera at the VLTI lab (Gitton et al. 2004). These correcting these residual aberrations can drastically improve the Strehl, in worst cases we measured that a correction of the 12 lowest order Zernikes modes beyond defocus lead to Strehl increase from 15% to 85% on internal source. We found NCPA to be relatively static on a monthly timescale (change are less than 20 nm rms per mode). However, all the tools are now in place for a regular NCPA monitoring and correction update in order to provide high-Strehl down to the IRIS camera.

NCPA control for GRAVITY science The IRIS camera provides a common NCPA reference to all VLTI instruments but it does not cover the full non-common path down to the science arm of GRAVITY. We know that the optical path in the GRAVITY cryostat crosses many optical elements, including off-axis parabolas that are prone to induce astigmatisms. For this reason, we are not satisfied with the IRIS NCPA but have a strong motivation to correct the aberrations down to the science fiber of the instrument. For the NCPA measurement, we use the harmonic modulation method to the fiber injection. However, the fiber injection is much more sensitive to the tip-tilt jitter induced by turbulence in the VLTI tunnels than a field imager like IRIS. Developments are in progress to provide a reliable measure and correction of NCPA down to the Science arm of GRAVITY, at least for the lowest orders (defocus, astigmatisms).

Dark hole Moreover, limiting the starlight smearing by a correction of NCPA is not the end of the high-contrast story. We are also investigating wavefront control techniques to further reduce the injection of starlight in the fiber when observing an off-axis exoplanet (Lacour et al. 2025). The technique uses iterative measurement and correction to dig a "dark-hole" where starlight is depleted specifically at the fiber position. Early tests during technical time confirmed that we can use the flux of each telescope to develop a fibered-speckle-nulling technique adapted to GRAVITY+. However, we are working on a more ambitious algorithm that would use the information included in the visibilities on the six interferometric baselines to determine the optimal phase and amplitude of the speckle under the fibers, and null it using commands to GPAOs. This path is very promising and would be the first ever "interferometric dark-hole". Altogether, when operational, we can expect these instrumental developments to lead to exoplanet detection limits of a few 10^{-6} down to 60 mas separation (Pourré et al. 2024).

3.2 Gaia DR4

As already mentioned, GRAVITY is more efficient when observing exoplanets whose position is constrained by previous observations. In December 2026, the Gaia Data Release 4 is expected to bring thousands of discoveries of exoplanet candidates with a peak sensitivity at semi-major axes around 2 astronomical units. A powerful synergy is expected with GRAVITY+ that would be able to observe the closest and the youngest candidates in our galactic neighborhood via direct imaging. Given the enhanced sensitivity of GRAVITY+, the Gaia-GRAVITY+ synergy might allow for detailed characterization of the mass, orbit and atmosphere of numerous new directly-imaged Jupiters and super-Jupiters.

4 Conclusions

The GRAVITY+ upgrade, particularly the new adaptive optics for the UTs, is delivering on all its promises. It already allows for going one step further in the atmosphere characterization of the brightest exoplanets, and allows for observation of fainter and fainter sub-stellar companions. Developments dedicated to high-contrast are still in progress and prepare the instrument for a major harvest of new directly imaged exoplanets thanks to the next release of the Gaia space telescope.

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*Available at `http://www.jmmc.fr/aspro`