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Hunting Exoplanets with Single-Mode Optical Interferometry

GRAVITY Collaboration (see page 20)

The GRAVITY instrument was primarily conceived for imaging and astrometry of the Galactic centre. However, its sensitivity and astrometric capabilities have also enabled interferometry to reach a new domain of astrophysics: exoplanetology. In March 2019, the GRAVITY collaboration published the first spectrum and astrometry of an exoplanet obtained by optical interferometry. In this article, we show how this observation is paving the way to even more exciting discoveries — finding new planets, and characterising their atmospheres.

New opportunities, new challenges

With the 2019 Nobel Prize, jointly awarded to Michel Mayor and Didier Queloz, the field of exoplanet research received worldwide recognition. It is true that for the first 20 years, the domain was more akin to a giant search for Easter eggs. The rarity of each discovery meant it had a major impact. The field was later significantly boosted by the space-based missions CoRoT (Convection, Rotation and planetary Transits), Kepler and now TESS (Transiting Exoplanet Survey Satellite), resulting in the discovery of thousands of exoplanets, and the development of a large community including many young scientists. The success of transit photometry, accompanied by a steady increase in the capabilities of stable high-precision radial velocity instruments — in which ESO has invested significantly; for example, the High Accuracy Radial velocity Planet Searcher (HARPS) and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) — now allows the analysis of the mass-separation distribution of planets, revealing gaps such as the hot Neptune desert (Neptune-sized planets within ~ 1 astronomical unit).

The next challenge in the field is the characterisation of exoplanetary atmospheres through spectroscopy. Until now, the technique has been dominated by high-resolution spectroscopy of evaporating atmospheres. With the CARMENES instrument (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs), for example, it is possible to constrain the level of atmospheric evaporation from the observation of a He I line (Alonso-Floriano et al., 2019). However, transit spectroscopy is limited to probing the upper atmosphere, and is inherently constrained by the duration of the transit. In the long term, the most promising technique is direct spectroscopy, where the light of the planet (either reflected light or thermal emission) is directly imaged on a spectrograph.

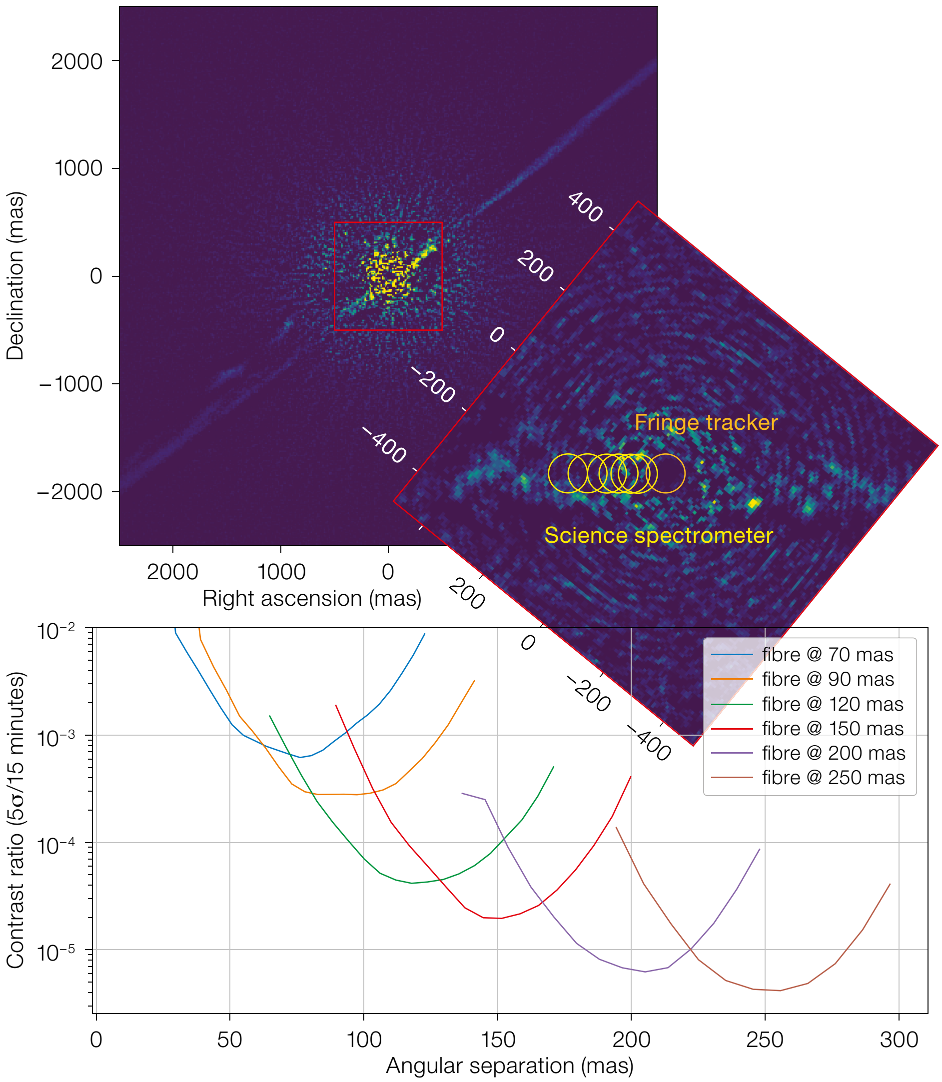

Figure 1. Upper panels: SPHERE observations of AU Mic (data from the InfraRed Dual-band Imager and Spectrograph [IRDIS] and the infrared Integral Field Spectrograph [IFS]; Boccaletti et al. 2018). Over-plotted on the IFS observation are the GRAVITY single-mode fibres. The sizes of the circles correspond to the field of view of GRAVITY. The fringe-tracker fibre is situated on the star, while the spectrometer's fibre is positioned at separations between 70 and 250 mas to the south-east of the star. From each position of the fibre, a 5-σ dynamic range is extracted and is plotted on the contrast curve. At 120 mas, a dynamic range of 4×10^{-5} is achieved. At 250 mas, the dynamic range is 4×10^{-6} (13.5 magnitudes).

This is where GRAVITY enters the field. A good exoplanet imager must have two main characteristics: an instrumental capability to remove the stellar diffraction pattern (to decrease the photon noise), and a numerical capability to remove the stellar speckles (to distinguish the planet). On an instrument like the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument, the former is done by means of a coronagraph, while the latter uses angular or spectral differential imaging techniques (ADI and SDI). On GRAVITY, an off-axis single-mode fibre plays the role of a coronagraph: placed on the planet, its limited field of view filters out the stellar light. The GRAVITY interferometer surpasses single-dish instruments in post-detection speckle removal: the angular resolution of about 3 milliarcseconds (mas) yields an unprecedented capability to distinguish speckles from planetary photons.

GRAVITY as a planet hunter

GRAVITY's high dynamic range at angular separations as small as 100 mas is obtained thanks to this exquisite post-processing. Figure 1 shows GRAVITY observations of the star AU Mic. The disc of AU Mic has prominent structures, which are resolved with SPHERE (Boccaletti, Thalmann & Lagrange, 2015). GRAVITY looks for point-like sources, of size smaller than its interferometric resolution (< 3 mas). Larger objects are not seen in the coherent flux of the interferometer.

The disadvantage of the single-mode interferometer is its field of view, which is given by the diffraction limit of the telescope (60 mas in the *K*-band for the VLT Unit Telescopes). Therefore, while the fringe tracker fibre stays on the star, the science fibre (which feeds the spectrograph) is placed at different positions across the disc. This is how GRAVITY hunts for exoplanets; it dithers the position of the fibre to cover a large area. In the case of AU Mic, we took advantage of the fact that we are only looking for a planet along an edge-on disc, so we only had to scan one line, thereby minimising the required telescope time.

In the resulting dataset, which covers only the south-eastern part of the disc, no detection was made. The dynamic range achieved by GRAVITY, with 15-minute exposures, is 11 magnitudes at 120 mas (5-σ). At 250 mas the dynamic range is even higher, reaching 13.5 magnitudes. This is several magnitudes fainter than what was achieved with aperture masking (Gauchet et al., 2016), and a completely new domain compared to what could be done with ADI and SDI techniques on a single 8-metre telescope.

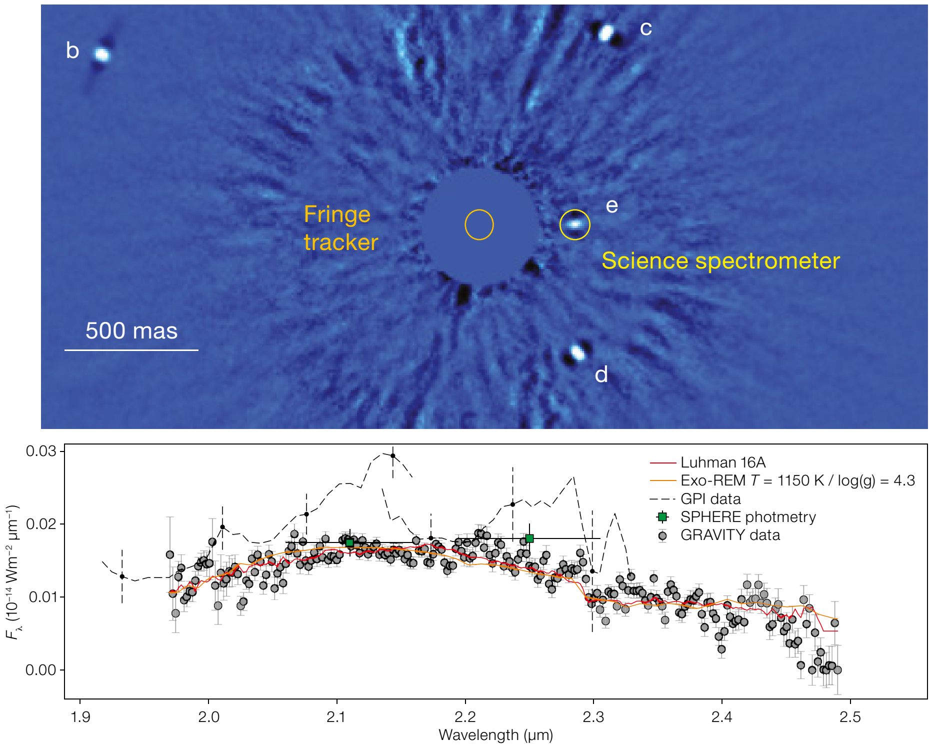

Figure 2. Upper panel: SPHERE/IRDIS image of HR8799 acquired with a broadband *H*-filter (from Wertz et al., 2017). As in Figure 1, we put the fringe-tracker fibre on the star. The science spectrometer fibre is on HR8799e. The sizes of the circles correspond to the GRAVITY field of view. Below: GRAVITY *K*-band spectrum of HR8799e at spectral resolution 500 (grey points) after 2 hours of integration. The dashed curve is the *K*-band Gemini Planet Imager (GPI) spectrum from Greenbaum et al. (2018), showing speckle contamination. (GRAVITY Collaboration et al., 2019).

GRAVITY as a way to characterise exoplanet atmospheres

In addition to its dynamic range, GRAVITY's angular resolution yields i) precise astrometry (between 10 and 100 µas) and ii) *K*-band spectra mostly unbiased by stellar light. Fortunately, such near-infrared spectra are rich in many molecular absorption lines: for example, H_2O, CO, CO_2, CH_4, N_2O. We applied this to HR8799e in GRAVITY Collaboration et al. (2019). HR8799e is the innermost object in a multi-planetary system. The angular separation to its host star is 380 mas, and the contrast is close to 11 magnitudes in the *K*-band. The young planet has an effective temperature of 1150 K, still hot from its formation. The spectra, shown in the bottom panel of Figure 2, show the CO absorption bands — no CH_4 absorption is detected. This gives clues that help to characterise the atmosphere. The difficulty in interpreting the data lies in the complex physical processes at work. Radiative transfer is used to derive the pressure-temperature curves, but clouds at different altitudes, with various compositions and possibly also heterogeneous, modify the temperature distribution. Chemical disequilibrium also adds complexity, with the necessity to add chemical timescales and mixing coefficients. In short, models need to be challenged by observations, and GRAVITY data is meeting that challenge.

In the near future, following the recent upgrade of GRAVITY's high-resolution grism, a resolution of 4000 will be achievable on exoplanets — a significant increase compared to the previous resolution of 500 (because of limited sensitivity). GRAVITY will therefore continue to challenge models of exoplanetary atmospheres, requiring simulations with more resolution and more complex chemical processes. One exciting prospect, for example, is the detection of C_{13} isotopes (Mollière & Snellen, 2019). In parallel, the recent development of atmospheric parameter retrieval is an exciting new technique, which performs better than fitting a grid of models. The aim is to obtain direct estimates of atomic ratios. One of them, the atmospheric C:O ratio, is currently believed to be a key tracer of an exoplanet's formation history (Öberg, Murray-Clay & Bergin, 2011). With GRAVITY, we will soon show that we are able to measure this C:O ratio (GRAVITY Collaboration et al., in press).

Acknowledgements

See page 23.

References

Alonso-Floriano, F. J. et al. 2019, A&A, 629A, 110
Boccaletti, A., Thalmann, C. & Lagrange, A. M. 2015, Nature, 526, 230
Boccaletti, A. et al. 2018, A&A, 614A, 52B
Gauchet, L. et al. 2016, A&A, 595A, 31G
GRAVITY Collaboration et al. 2019, A&A, 623, 11
Greenbaum, A. Z. et al. 2018, AJ, 155, 226G
Mollière, P. & Snellen, I. A. G. 2019, A&A, 622A, 139
Öberg, K. I., Murray-Clay, R. & Bergin, E. A. 2011, ApJ, 743L, 16O
Wertz, O. et al. 2017, A&A, 598, A83

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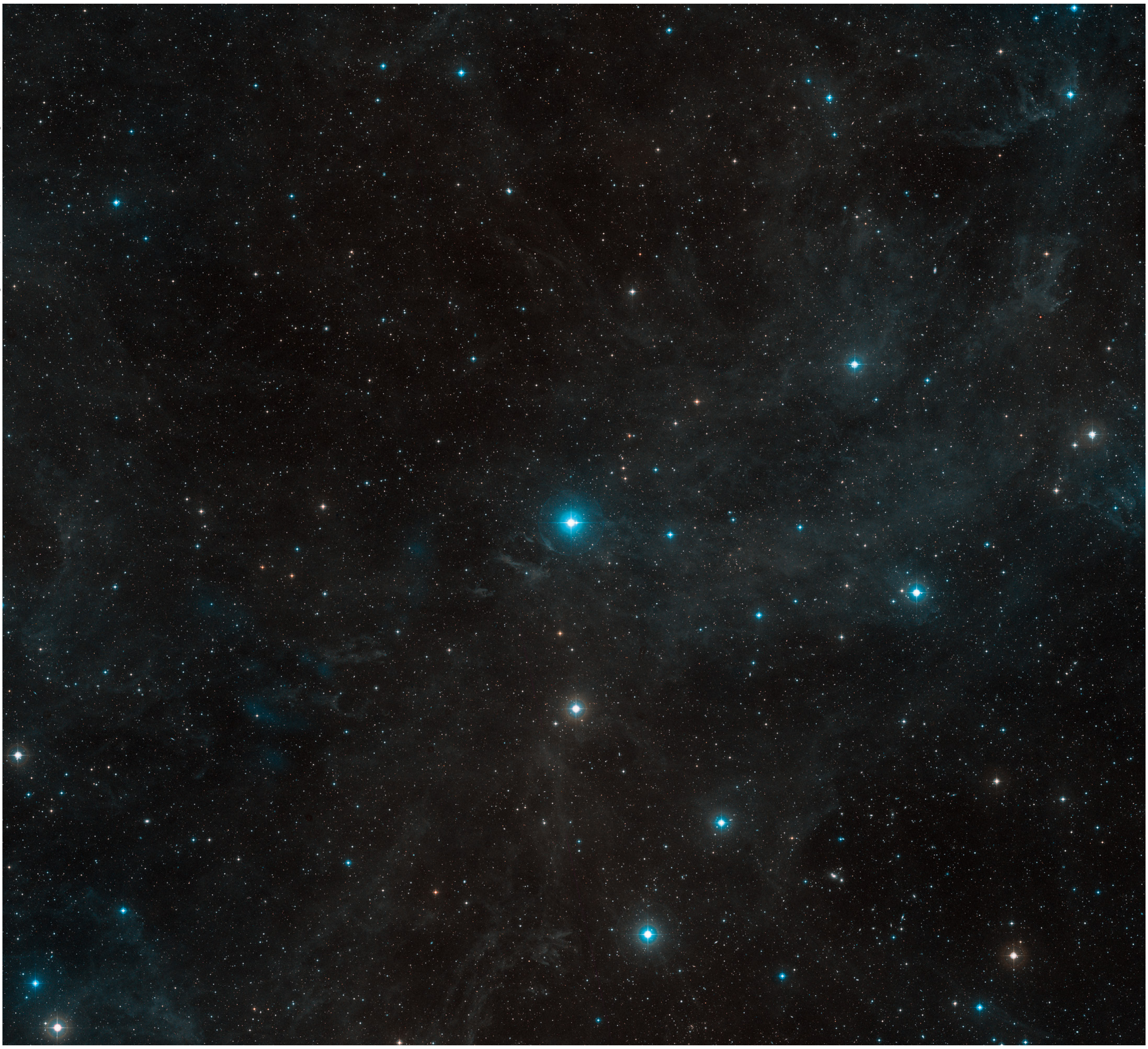

Wide-field image showing the field in the constellation of Pegasus centred on HR8799.