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GRAVITY Science Verification

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In the time between successfully commissioning an instrument and before offering it in the Call for Proposals for the first time, ESO gives the community at large an opportunity to apply for short Science Verification (SV) programmes. In 2016, ESO offered SV time for the second-generation Very Large Telescope Interferometer instrument GRAVITY. In this article we describe the selection process, outline the range of science cases covered by the approved SV programmes, and highlight some of the early scientific results.

ESO issued a call for SV on the Auxiliary Telescopes (ATs) in March 2016, just after the on-sky performance of GRAVITY was established (GRAVITY Collaboration, 2017) and the Science Operations team had been trained in operating the instrument. In total, 43 proposals were received. The SV proposals were evaluated by a team led by Jean-Philippe Berger, who was the Very Large Telescope Interferometer (VLTI) Programme Scientist at the time. The panel consisted of members of the Instrument Operation Team and the GRAVITY consortium. Their main task was to assess the feasibility and scientific merits of each project, and later to acquire the observations and carry out the data reduction. All information regarding SV can be found on the GRAVITY SV page[1].

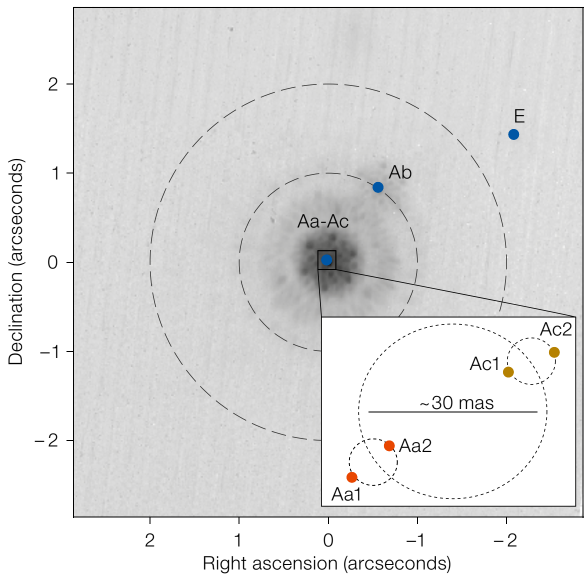

Figure 1. This is a Sparse Aperture Masking image of the system HD 93206 taken with NACO using the K_s filter. The position of the Aa-Ac, Ab and E components are represented by blue dots. Two concentric dashed rings encircle the central 2–4 arcseconds around HD 83206A. The inset diagram shows the quadruple system Aa-Ac, which is the main target of the observations.

20 programmes were selected to showcase the spectro-imaging capabilities of GRAVITY and to enable its performance — in terms of sensitivity, wide simultaneous spectral coverage and improved spatial information — to be compared to the Astronomical Multi-BEam combineR (AMBER), the VLTI instrument it most closely resembles. Two SV runs of nine nights each were scheduled in June and September 2016 and observations were carried out in service mode by the SV team. The instrument operations were smooth, but it was challenging to complete all the programmes in the allocated time as they required multiple changes to the AT configurations. Despite this, there was no substantial loss of time and ultimately 14 programmes were considered fully or almost completed, with six programmes either partially completed or not completed. We present some highlights from four SV programmes here.

The quadruple massive stars in HD 93206

Almost all massive stars are found in multiple systems: Sana et al. (2014) showed that 90 % of massive stars have at least one companion, while 30 % belong to triple or higher-degree systems. In addition to detecting and cataloguing systems for statistical studies, it is necessary to investigate individual systems to test massive star formation scenarios. The late-O/early-B type system HD 93206, also known as QZ Car, is the most massive quadruple star system known, totalling 90 $M_\odot$. The GRAVITY observations of HD 93206 (Programme ID 60.A-9175, Principal Investigator [PI]: Sanchez-Bermudez) were used to improve on NAOS–CONICA (NACO) sparse aperture masking (SAM) observations (Figure 1). The reconstructed GRAVITY image shows Aa and Ac clearly but does not resolve each component as a binary (Figure 2). Previous observations with the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER) and the less precise NACO/SAM separation for Aa-Ac are also shown. The new analysis excludes the presence of a companion up to 5 magnitudes fainter in this 150-milliarcsecond field of view.

In addition to spatially resolving Aa-Ac as a binary, GRAVITY's spectroscopic resolution allowed two lines to be detected: hydrogen Brγ lines (2.1661 μm), which trace shocks in the winds from the hot stars, and helium lines (2.058 μm & 2.112 μm), which are photospheric. These GRAVITY observations show that the Brγ emission is very compact and does not result from the interaction of winds from Aa and Ac. An alternate explanation is that the emission results from wind interactions within the Aa and Ac binaries. Future observations using GRAVITY with the Unit Telescopes (UTs) should result

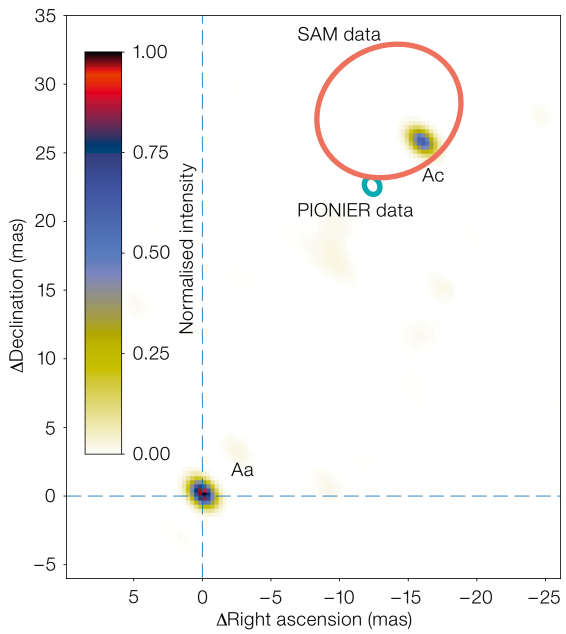

Figure 2. BiSpectrum Maximum Entropy Method (BSMEM) reconstructed interferometric image of HD 93206A. The components of the outer binary Aa-Ac are labelled on the figure. The colour scale represents the normalised intensity. Cyan and red ellipses show the 1-σ positions of the Ac component based on PIONIER and NACO observations respectively (Sana et al., 2014). The positional difference between the PIONIER and GRAVITY epochs is due to orbital motion.

in better sensitivity and enable the detection of a weak interferometric signal in Brγ within the Aa and/or Ac binaries.

The evolved binary star Ups Sgr

Ups Sgr is an interacting binary in an advanced stage of evolution, in which the stripped donor has lost its hydrogen envelope and is now experiencing a second episode of mass loss during core helium burning. The spectroscopic binary has an orbital period of 138 days (Koubsky et al., 2006). The binary is also surrounded by a dusty torus with an inner rim diameter of 20 milliarcseconds, as detected by the MID-infrared Interferometric instrument (MIDI) on the VLTI (Netolický et al., 2009). Bonneau et al. (2011) detected over-resolved Hα emission with the Centre for High Angular Resolution Astronomy (CHARA) interferometer using the Visible spEctroGraph and polArimeter (VEGA).

This system was imaged by GRAVITY (Programme ID 60.A-9177, PI Gies) and complemented by *H*-band data from the Michigan InfraRed Combiner (MIRC) on CHARA. Preliminary results indicate that GRAVITY can resolve the inner binary with a separation of a few milliarcseconds. A significant amount of light (~ 60–70 %) is detected from an over-resolved circumbinary disc; the flux ratio between the disc and the binary shows a chromatic wavelength dependence across the spectral channels. An additional asymmetry in the system was detected, likely from resolved structure in the inner region of the disc. The team is in the process of reconstructing images while simultaneously fitting for binary separation, with the goal of producing snapshots of the system at different orbital phases.

The complex young stellar binary system CO Ori

Programme 60.A-9159 (PI Davies) used the short baseline configuration (8–30 m) of the ATs to observe both components of the CO Ori young stellar object binary system. The single-field mode was used to observe the primary (*K* = 3.0 magnitudes). Located 2 arcseconds away, the secondary (*K* = 6.0) required GRAVITY's unique dual-field mode and was observed by the GRAVITY spectrograph while the primary was used for fringe tracking. Both the circumprimary and circumsecondary *K*-band emission were successfully spatially resolved for the first time. This confirmed the previous result from Rodgers et al. (2003) that the secondary star is responsible for the Brγ emission observed towards the system. Together with GRAVITY's detection of circumsecondary continuum emission, the presence of this line (typically associated with the accretion process in young stars) provides strong evidence for the presence of a circumsecondary accretion disc.

The team is using geometrical models to determine the orientation of the circumprimary and circumsecondary material. The continuum closure phases for both binary components provide no strong indication of a deviation from a centrosymmetric brightness distribution at the distances probed. The team is therefore focusing their modelling on the continuum visibilities. Their results indicate the presence of a disc around the primary CO Ori A (full width at half maximum [FWHM] = 2.31 ± 0.04 milliarcseconds; inclination, *i* = 30.2 ± 2.2 degrees; position angle [PA] = 40.6), while the circumsecondary emission more likely comprises a disc (FWHM = 0.96 ± 0.55) and an extended halo component. This halo component is likely attributed to scattered light (for example, Pinte et al., 2008).

The primary science goal of this programme was to determine the relative orientation of the discs in the binary system. However, the *K*-band emission from CO Ori B was more compact than anticipated and astronomers were unable to determine the orientation of the circumsecondary emission. Instead, efforts were redirected to the secondary scientific aim of probing the origin of the variable extinction (UX Ori phenomena) associated with CO Ori A.

The inclination of the circumprimary emission is below that found for the discs of other UX Ori-type stars (*i* ~ 30–70 degrees; Eisner et al., 2004; Pontoppidan et al., 2007; Chapillon et al., 2008; Kreplin et al., 2013; Vural et al., 2014; Kreplin et al., 2016). Thus, rather than emanating from a disc (for example, Natta et al., 1997), CO Ori A provides the first indication that in some cases the UX Ori phenomena may be attributed to irregularities in a dusty outflow (for example, Tambovtseva & Grinin, 2008). These results are presented in greater detail in Davies et al. (2017).

The planet-hosting debris disc around β Pic

Medium-resolution GRAVITY observations of the young star β Pic (HD 39060,

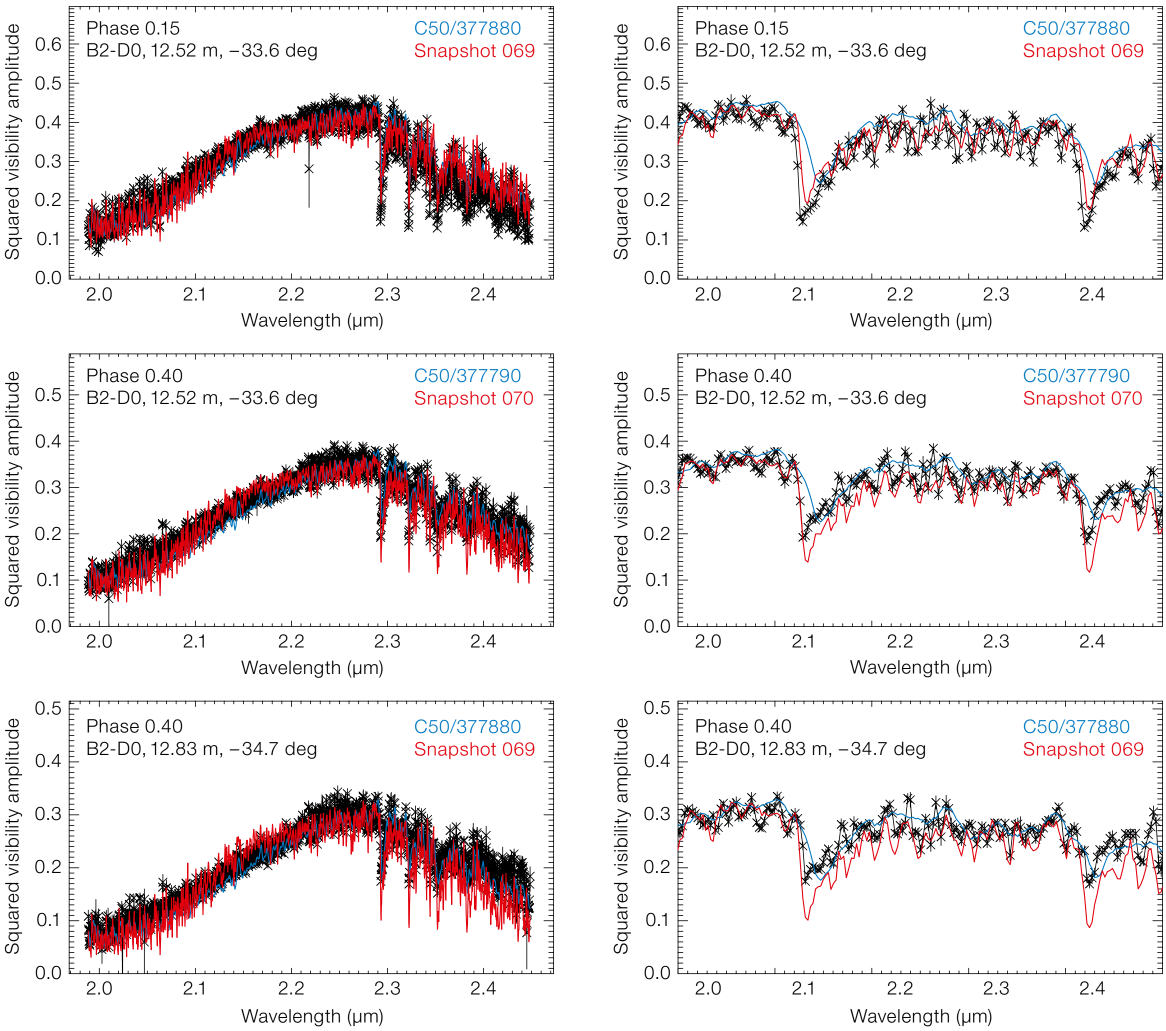

Figure 3. GRAVITY observations of the Mira star R Peg. Left: Visibilities (black) of R Peg in June, September, and November 2016 at visual phases 0.15, 0.40 and 0.65. Also shown are predictions by the best-fit CODEX models (blue) and RHD simulations (red). The wavelength range covers 1.98–2.45 µm and corresponds to the full wavelength coverage of the GRAVITY instrument (Wittkowski et al., in preparation). Right: Zooming in on the wavelength range around the CO (2-0 and 3-1) bandheads at 2.29 µm and 2.32 µm.

A6V, 19.3pc, ~ 12 Myr) were carried out using the compact VLTI configuration (Programme ID 60.A-9161, PI Defrère). β Pic is a prime target for understanding planetary system formation and evolution. Since the discovery of its planetary system (Smith & Terrile, 1984) successive generations of telescopes have reported the detection of an edge-on debris disc. The disc has several distinctive features suggestive of a multiple-belt system (Telesco et al., 2005); star-grazing comets arranged into two families (Beust et al., 1990; Kiefer et al., 2014); circumstellar gas (for example, Roberge et al., 2006; Dent et al., 2014); and a planetary companion (~ 10 M_{Jup}) orbiting the star with a semi-major axis of ~ 9 astronomical units (au) (Lagrange et al., 2009). The existence of other planets also seems likely (Freistetter et al., 2007) and may explain several asymmetries identified in the debris disc, including a warp at ~ 50 au, inclined by approximately 4 degrees with respect to the outer disc (Augereau et al., 2001; Lagrange et al., 2012).

Over the past few years, the close environment (less than a few au) of β Pic has been the focus of several studies trying to detect a predicted sub-stellar companion. In particular, closure phase measurements with AMBER and PIONIER excluded the presence of companions a few hundred times fainter than the central star at angular separations up to approximately 100 milliarcseconds (i.e., a brown dwarf of about 30 M_{Jup} at the age of β Pic; Absil et al., 2010). No companion has been detected at the current precision level, although accurate squared visibilities obtained with PIONIER have revealed the presence of resolved circumstellar emission, with an integrated brightness amounting to approximately 1.4 % of the stellar brightness in the *H*-band (Defrère et al., 2012).

If the scattering of stellar light in the outer disc is seen edge-on, it may help to explain the spectral shape of the measured excess. However, current models fail to reproduce the total value of this excess, and hot material must also be present in the innermost region of the planetary system. The prevailing scenario is the presence of hot exozodiacal dust as proposed for older A-type stars (for example, Ertel et al., 2014).

However, the exact amount of hot dust, its location and its chemical properties remain unclear, particularly due to the lack of multi-wavelength information. GRAVITY has a crucial role to play here by providing the first medium-resolution spatially resolved observations of the inner planetary system. The SV data confirm the presence of resolved circumstellar emission that depends on the wavelength and the baseline orientation, unlike previous observations of this excess obtained in the *H*-band (Defrère et al., 2012). Thorough radiative-transfer modelling is currently underway to produce a disc model that will fit the observed visibilities and reveal the nature of this puzzling excess emission.

The Mira-type star R Peg

Low- to intermediate-mass stars, including our Sun, evolve into red giants and subsequently into asymptotic giant branch (AGB) stars. Mass loss increases during AGB evolution and eventually dominates the subsequent stellar evolution. AGB mass loss is driven by interplay between pulsations that extend the atmosphere, dust formation in the extended atmosphere, and radiation pressure on the dust. However, the details of these interrelated processes remain unknown.

Recent one-dimensional dynamic model atmospheres, based on self-excited pulsation models of oxygen-rich Mira stars, predicted a regular sinusoidal variation of the photospheric radius and the irregular chaotic variability of the outer molecular layers (Cool Opacity-sampling Dynamic EXtended [CODEX] models; Ireland et al., 2008, 2011). Similarly, three-dimensional radiation hydrodynamic (RHD) simulations of AGB stars by Freytag & Höfner (2008) showed shock waves that are overall roughly spherically expanding, and are similar to those from the one-dimensional models with certain additional non-radial structures. Comparisons by Wittkowski et al. (2016) of AMBER data with both CODEX and RHD models showed that predictions by both types of models are indeed consistent and can explain observations at individual epochs. PIONIER imaging observations by Wittkowski et al. (2017) confirmed the predicted effects of non-radial structures on clumpy dust formation.

Early long-term narrow-band monitoring of Mira variables at the Palomar Testbed Interferometer by Thompson et al. (2002) showed the expected sinusoidal variation in a near-continuum bandpass for two sources with different phase lags. Since then, this predicted variability over a stellar cycle has not been convincingly confirmed. AMBER observations, along with observations from other facilities, showed agreement with CODEX models at individual epochs but could not convincingly show the longer-term variability.

GRAVITY observations promised to deliver stronger observational constraints at any epoch, allowing us to verify the model-predicted variability of the visibility spectra. This expectation was based on the high spectral resolution of GRAVITY, which can be reached over the whole *K*-band; the higher expected S/N on the target visibility spectra due to the longer integration times on the science spectrometer; and the higher expected accuracy of calibrated visibilities, due to the better stability of the instrument as compared to previous campaigns with AMBER.

The first such observations were attempted by a team led by Markus Wittkowski, Gioia Rau and Andrea Chiavassa (Programme ID 60.A-9176). The Mira variable R Peg was observed in June, September and November 2016. The latest epoch was part of the follow-up programme 098.D-0647 (PI Wittkowski). Calibrator star observations interleaved the R Peg observations. Data were obtained in the high spectral resolution and split polarisation modes, and were reduced using the GRAVITY pipeline (version 1.0.5). The data obtained with the science spectrometer were compared to those from the faster low-resolution fringe tracker and gave a consistent height of the calibrated visibility. This confirms a good absolute calibration of the visibility data.

Figure 1 shows preliminary results of the visibility data covering the full *K*-band for the example of one baseline at the three epochs. The best-fit CODEX model atmospheres as well as the best-fit three-dimensional radiation hydrodynamic (RHD) simulations by Freytag & Höfner (2008) are also shown. These fits were obtained in the same way as for the AMBER data of AGB stars (Wittkowski et al., 2016). The projected baseline lengths and position angles at the three epochs are very similar. These preliminary results suggest a decreasing visibility at a near-continuum bandpass around 2.25 μm along visual variability phases 0.15, 0.40, and 0.65, which corresponds to an increasing continuum radius. At the same time, the visibility dip at the CO bandheads relative to the nearby near-continuum decreases along these phases. This suggests a decreasing contribution by extended CO layers. Furthermore, the comparison to one- and three-dimensional dynamic model atmospheres shows a good agreement between the observations and models in the shape of the visibility function. Note that these are preliminary results and a more detailed analysis will appear in Wittkowski et al. (in preparation).

This preliminary analysis promises that GRAVITY will provide measurements of the pulsation of the photosphere and extended atmosphere of AGB stars in unprecedented detail. Comparisons to the newest models (for example, Freytag et al., 2017) will enable further insights into the processes of convection and pulsation in these atmospheres.

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Links

[1] GRAVITY Science Verification: https://www.eso.org/sci/activities/vltsv/gravitysv.html