GRAVITY: Observing the Universe in Motion

Frank Eisenhauer[1]
Guy Perrin[2,10]
Wolfgang Brandner[3]
Christian Straubmeier[4]
Karine Perraut[5]
António Amorim[6]
Markus Schöller[9]
Stefan Gillessen[1]
Pierre Kervella[2,10]
Myriam Benisty[3]
Constanza Araujo-Hauck[4]
Laurent Jocou[5]
Jorge Lima[6]
Gerd Jakob[9]
Marcus Haug[1]
Yann Clénet[2,10]
Thomas Henning[3]
Andreas Eckart[4]
Jean-Philippe Berger[5,9]
Paulo Garcia[6]
Roberto Abuter[9]
Stefan Kellner[1]
Thibaut Paumard[2,10]
Stefan Hippler[3]
Sebastian Fischer[4]
Thibaut Moulin[5]
Jaime Villate[6]
Gerardo Avila[9]
Alexander Gräter[1]
Sylvestre Lacour[2,10]
Armin Huber[3]
Michael Wiest[4]
Axelle Nolot[5]
Pedro Carvas[6]
Reinhold Dorn[9]
Oliver Pfuhl[1]
Eric Gendron[2,10]
Sarah Kendrew[3]
Senol Yazici[4]
Sonia Anton[6,8]
Yves Jung[9]
Markus Thiel[1]
Élodie Choquet[2,10]
Ralf Klein[3]
Paula Teixeira[6,9]
Philippe Gitton[9]
David Moch[1]
Frédéric Vincent[2,10]
Natalia Kudryavtseva[3]
Stefan Ströbele[9]
Eckhard Sturm[1]
Pierre Fédou[2,10]
Rainer Lenzen[3]
Paul Jolley[9]
Clemens Kister[1]
Vincent Lapeyrère[2,10]
Vianak Naranjo[3]
Christian Lucuix[9]
Reiner Hofmann[1]
Frédéric Chapron[2,10]
Udo Neumann[3]
Leander Mehrgan[9]
Oliver Hans[1]
Gérard Rousset[2,10]
Jose Ramos[3]
Marcos Suarez[9]
Reinhard Lederer[1]
Jean-Michel Reess[2,10]
Ralf-Rainer Rohloff[3]
Pierre Haguenauer[9]
Hendrik Bartko[1]
Arnaud Sevin[2,10]
Karl Wagner[3]
Jean-Louis Lizon[9]
Sebastian Rabien[1]
Claude Collin[2,10]
Gert Finger[9]
Richard Davies[1]
Daniel Rouan[2,10]
Markus Wittkowski[9]
Katie Dodds-Eden[1]
Denis Ziegler[2,10]
Frédéric Cassaing[7,10]
Henri Bonnet[9]
Mark Casali[9]
Reinhard Genzel[1]
Pierre Lena[2]

1 Max-Planck Institute for Extraterrestrial Physics, Garching, Germany
2 LESIA, Observatoire de Paris, CNRS, UPMC, Université Paris Diderot, Meudon, France
3 Max-Planck Institute for Astronomy, Heidelberg, Germany
4 Physikalisches Institut, University of Cologne, Germany
5 UJF–Grenoble 1/CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble, France
6 Laboratório de Sistemas, Instrumentação e Modelação em Ciências e Tecnologias do Ambiente e do Espaço (SIM), Lisbon and Porto, Portugal
7 ONERA, Optics Department (DOTA), Châtillon, France
8 Centro de Investigação em Ciências Geo-Espaciais, Porto, Portugal
9 ESO
10 Groupement d'Intérêt Scientifique PHASE (Partenariat Haute résolution Angulaire Sol Espace) between ONERA, Observatoire de Paris, CNRS and Université Paris Diderot

GRAVITY is the second generation Very Large Telescope Interferometer instrument for precision narrow-angle astrometry and interferometric imaging. With its fibre-fed integrated optics, wavefront sensors, fringe tracker, beam stabilisation and a novel metrology concept, GRAVITY will push the sensitivity and accuracy of astrometry and interferometric imaging far beyond what is offered today. Providing precision astrometry of order 10 microarcseconds, and imaging with 4-milliarcsecond resolution, GRAVITY will revolutionise dynamical measurements of celestial objects: it will probe physics close to the event horizon of the Galactic Centre black hole; unambiguously detect and measure the masses of black holes in massive star clusters throughout the Milky Way; uncover the details of mass accretion and jets in young stellar objects and active galactic nuclei; and probe the motion of binary stars, exoplanets and young stellar discs. The instrument capabilities of GRAVITY are outlined and the science opportunities that will open up are summarised.

Fundamental measurements over a wide range of fields in astrophysics

Much as long-baseline radio interferometry has tone, GRAVITY infrared (IR) astrometry, with an accuracy of order 10 microarcseconds and phase-referenced imaging with 4-milliarcsecond resolution, will bring a number of key advances (Eisenhauer et al., 2008). GRAVITY will carry out the ultimate empirical test to show whether or not the Galactic Centre harbours a black hole (BH) of four million solar masses and will finally decide if the near-infrared flares from Sgr A* originate from individual hot spots close to the last stable orbit, from statistical fluctuations in the inner accretion zone or from a jet. If the current hot-spot interpretation of the near-infrared (NIR) flares is correct, GRAVITY has the potential to directly determine the spacetime metric around this BH. GRAVITY may even be able to test the theory of general relativity in the presently unexplored strong field limit. GRAVITY will also be able to unambiguously detect intermediate mass BHs, if they exist. It will dynamically measure the masses of supermassive

BHs (SMBHs) in many active galactic nuclei, and probe the physics of their mass accretion, outflow and jets with unprecedented resolution. Furthermore, GRAVITY will explore young stellar objects, their circumstellar discs and jets, and measure the properties of binary stars and exoplanet systems. In short, GRAVITY will enable dynamical measurements in an unexplored regime, and it will increase the range and number of astronomical objects that can be studied with the Very Large Telescope Interferometer (VLTI) substantially. An overview of the key experiments that will become possible with GRAVITY is illustrated on the Telescopes and Instrumentation section page (p. 6, lower panel).

A unique combination with the VLTI

The VLTI is the largest array of 8-metre-class telescopes that explicitly included interferometry in its design and implementation. No other array is equipped with a comparable infrastructure. The VLTI, with its four 8-metre Unit Telescopes (UTs) and a total collecting area of 200 m^2, is the only interferometer to allow direct imaging at high sensitivity and high image quality. The VLTI is also the only array of its class offering a large (2-arcsecond) field of view and this unique capability will, for the first time, be utilised, providing simultaneous interferometry of two objects. This capability allows narrow-angle astrometry with a precision of order 10 microarcseconds. A second new and unique element of GRAVITY is the use of IR wavefront sensors to observe highly obscured objects suffering high extinction. GRAVITY is also the only instrument providing phase-referenced complex visibilities, which is a major advantage for the model independence and fiducial quality of interferometric maps. The combination of VLTI and GRAVITY will be the world-leading facility for many years to come.

Adaptive optics assisted interferometric imaging and astrometry

GRAVITY provides high precision narrow-angle astrometry and phase-referenced interferometric imaging in the astronomical *K*-band (2.2 μm). It combines the light

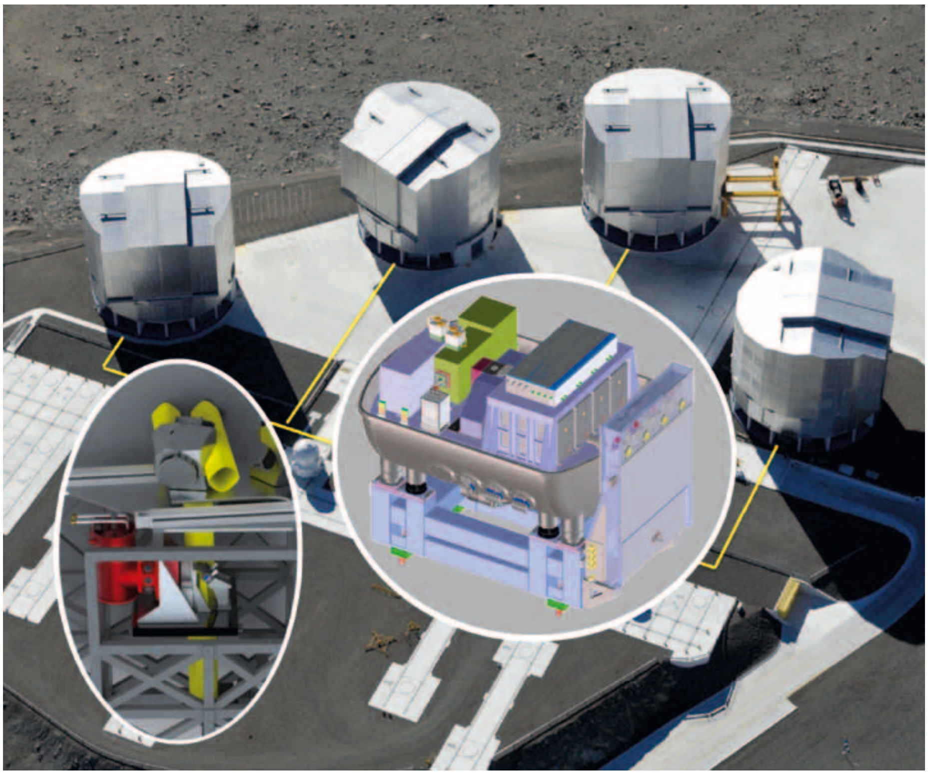
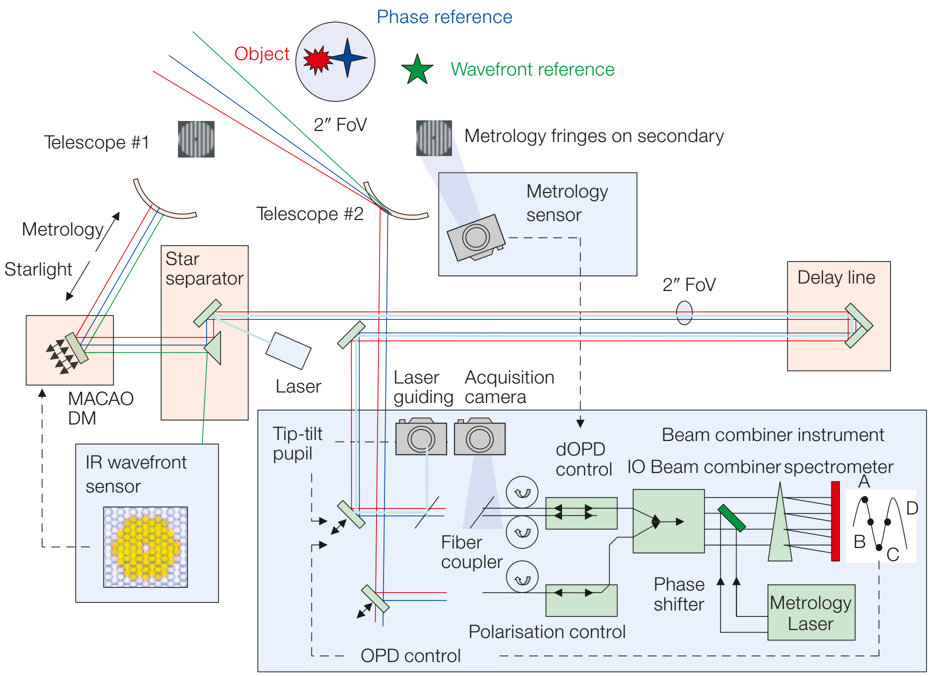


Figure 1. (Upper) GRAVITY at the VLT Interferometer. GRAVITY combines the light from four UT or AT telescopes, measuring the interferograms for six baselines simultaneously, with a maximum baseline of 200 metres. The insets depict the GRAVITY beam-combiner instrument (middle), which is located in the VLTI laboratory, and one of the four GRAVITY IR wavefront sensors (left) for each of the UTs.

Figure 2. (Lower) Working principle of GRAVITY. The beam-combiner instrument (bottom right) is located in the VLTI laboratory. The IR wavefront sensors (bottom left) are mounted on each of the four UTs. The laser metrology is launched from the beam combiner and is detected at each UT/AT (top middle).



from four UTs or Auxiliary Telescopes (ATs), measuring the interferograms from six baselines simultaneously (see Figure 1). The instrument has three main components: the IR wavefront sensors (Clénet et al., 2010); the beam-combiner instrument; and the laser metrology —system (Bartko et al., 2010). Figure 2 gives an overview of the GRAVITY instrument. For clarity, only two of the four telescopes — i.e. one out of six baselines — are shown.

The GRAVITY IR wavefront sensors will be mounted in the Coudé rooms of the UTs and will command the existing Multiple Application Curvature Adaptive Optics (MACAO) deformable mirrors. The system can work on either of the two beams (on-axis or off-axis) behind the PRIMA star separators. Any additional tip/tilt from the beam relay down to the VLTI laboratory will be corrected by a dedicated laser-guiding system. Low frequency drifts of the field and pupil will be corrected by GRAVITY's internal acquisition and guiding camera (Amorim et al., 2010). The interplay of these systems will guarantee an unperturbed and seeing-corrected beam at the entrance of the beam-combiner instrument in the VLTI laboratory. The interferometric instrument will work on the 2-arcsecond (for UTs) or 4-arcsecond (for ATs) VLTI field of view. Both the reference star and the science object have to lie within this field of view. The light of the two objects from the four telescopes is coupled (Pfuhl et al., 2010) into optical fibres for modal filtering, to compensate for the differential delay and to adjust the polarisation. The fibres feed two integrated optics beam combiners (Jocou et al., 2010) and the coherently combined light is dispersed in two spectrometers (Straubmeier et al., 2010). A low resolution spectrometer provides internal phase- and group-delay tracking (Choquet et al., 2010) on the reference star, and thus enables long exposure times on the science target. Three spectral resolutions with up to $R \sim 4000$ are implemented in the science spectrometer, and a Wollaston prism provides basic polarimetry.

GRAVITY will measure the visibility of the reference star and the science object simultaneously for all spectral channels, and the differential phase between the two objects. This information will be used for interferometric imaging exploring the complex visibilities, and for astrometry using the differential phase and group delay. All functions of the GRAVITY beam-combiner instrument are implemented in a single cryostat for optimum stability, cleanliness, and thermal background suppression. The internal path lengths of the VLTI and GRAVITY are monitored using dedicated laser metrology. The laser light is back-propagated from the beam combiner and covers the full beam up to the telescope spider above the primary mirror.

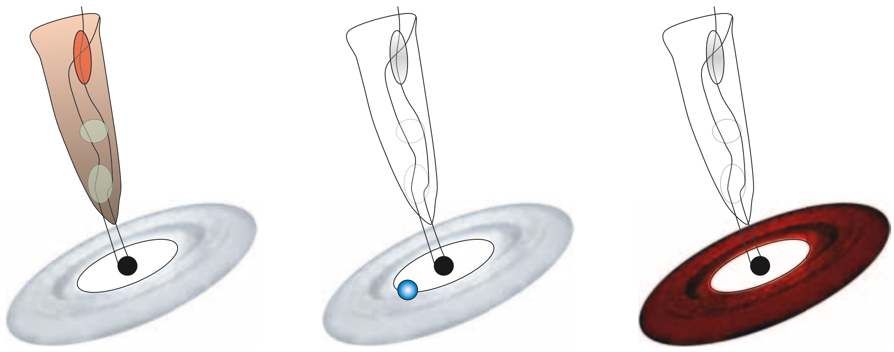
Highlights from the instrument development

A detailed description of GRAVITY's subsystems can be found elsewhere (Gillessen et al. [2010] and above references). Instead, we present a few highlights from the ongoing prototype development: the world's first *K*-band (2.2 μm) integrated optics beam combiner for four telescopes, a high-speed photon-counting IR detector, and a novel laser metrology concept.

GRAVITY's beam combiner is an integrated optics chip, the optical equivalent of a microelectronic circuit, which combines several functions in a single component. It combines the advantages of compactness and stability, and provides outstanding visibility accuracies. Integrated optics is widely used in telecommunications up to 1.6 μm, but does not cover the astronomically interesting *K*-band. GRAVITY has thus launched its own development programme between IPAG, LETI, and CIP to port the technology to longer wavelengths. Following a series of prototypes implementing individual functions, we now have the world's first *K*-band integrated optics beam combiner for four telescopes in hand (shown in Figure 3).

The second major breakthrough for GRAVITY is the recent success in the development of high-speed IR photon-counting detector arrays. All current astronomical IR fringe trackers and wavefront sensors suffer from the high readout noise of their detectors, which is ten or more electrons per pixel at frame rates of a few hundred Hz. The GRAVITY detectors overcome this noise barrier by avalanche amplification of the photoelectrons inside the pixels. Last year, SELEX-Galileo and ESO demonstrated for the first time a readout-noise of less

Figure 3. A recent breakthrough in integrated optics is shown (left) and an example image from the new avalanche photodiode detector arrays (right); both to be used in GRAVITY.



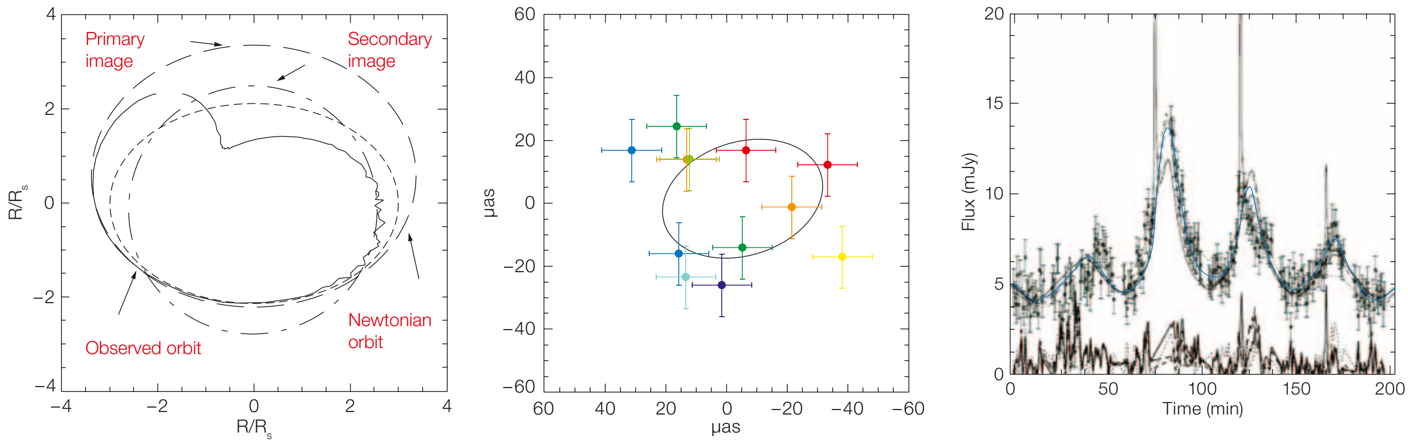


Figure 4. Uncovering the true nature of Sgr A* flares (upper three panels); probing spacetime close to the black hole event horizon (lower left); and measuring its spin and inclination (two lower right panels). GRAVITY will easily distinguish between the three most plausible flare scenarios: a jet (left), an orbiting hot spot (middle) and statistical fluctuation in the accretion flow (right). The detailed shape of the photo-centre orbit is dominated by general relativistic effects (lower left, from Paumard et al. 2008), and GRAVITY will thus directly probe spacetime close to the event horizon. The combination of time-resolved astrometry (lower middle) and photometry (lower right, from Hamaus et al., 2008) will also allow the spin and inclination of the BH to be measured.

than three electrons with their prototype detector array (see image in Figure 3). Based on this success, ESO and SELEX–Galileo are currently developing a next generation detector, which is tuned to GRAVITY's wavefront sensor and fringe tracker. Another example of a major breakthrough is in GRAVITY's laser metrology. It is based on a novel concept, and traces the starlight through the observatory, to allow the optical path to be measured at any desired point of the pupil up to the primary mirror. This concept and its implementation have been demonstrated in three technical runs at the VLTI.

Science cases for GRAVITY

In the following sections the science cases for GRAVITY are briefly outlined, beginning with the broad range of science opportunities that have opened up at the Galactic Centre of the Milky Way. The Galactic Centre is by far the closest galactic nucleus and the best studied SMBH (Genzel et al., 2010). There are still a number of fundamental open issues and just to name a few that we want to answer with GRAVITY: What is the nature of the flares in Sgr A*? What is the spin of a BH? How can we resolve the "Paradox of Youth" of the stars in its vicinity? Even tests of fundamental physics may come into reach with GRAVITY: Does the theory of general relativity hold in the strong field around SMBHs? Do BHs really have "no hair"?

Uncovering the true nature of the SgrA* flares

The Galactic Centre BH is surprisingly faint — its average luminosity is only about 10^{-8} of the Eddington luminosity, emitted predominantly at radio to sub-mm wavelengths. On top of this quasi-steady component there is variable emission in the X-ray and IR bands. Some of this variable emission comes as flares, typically a few times per day, lasting for about one to two hours, and reaching the brightness of massive main-sequence stars. The three most plausible explanations for the origin of these flares are: a jet with clumps of ejected material; hot spots orbiting a BH; or statistical fluctuations in the accretion flow (Figure 4). The jet model seems natural from the presence of jets in active galactic nuclei. The orbiting hot-spot model would be a natural explanation for the observed quasi-periodicity in the light curves of flares and associated changes of the IR polarisation. However, the long-term light curves are well described by a pure, red power-law noise, indicating that statistical fluctuations in the accretion flow are responsible for the observed variability. Time-resolved astrometric measurements with GRAVITY will settle the debate (Eckart et al., 2010). Even without pushing GRAVITY to its ultimate performance, the observed distribution of flare positions and its periodic variation will distinguish between these models.

Measuring spin and inclination of the Galactic Centre black hole

The mass of the Galactic Centre BH is well known from stellar orbits. If the currently favoured orbiting hot-spot model is correct, GRAVITY will take the next step and measure its spin and inclination.

These measurements are more difficult because the astrometric signature from the spin is a factor few less than the orbital motion and lensing effects. However, the combined signal from the periodic light curves and astrometry is much stronger. Already the simple correlation between the observed position variation and flux variability is giving the first insights into the source geometry. The next step is a simultaneous fit to the observed motion and light curve to quantify the underlying model parameters (Figure 4). Finally, the periodic flux can be used to trace the orbital phase to coherently co-add measurements from multiple flares, such that higher order signatures can be directly identified.

Resolving the Paradox of Youth of the Galactic Centre stars

Most stars in the central light-month of the Galactic Centre are young, massive early-type main sequence stars. It is currently not understood how these stars have formed or moved so close to the SMBH, because the tidal forces should have prevented *in situ* formation, and because these stars are too young to have migrated so far within the timescale of classical relaxation. Precise orbit measurements with GRAVITY offer a route to resolving this Paradox of Youth. In particular measurements of the orbital eccentricities can distinguish between the various scenarios. The currently favoured Hills scenario, in which massive binaries are scattered down to the BH and one component is ejected in a three-body interaction with the BH, will lead to predominantly high eccentricities. In contrast, the competing migration scenario, in which the stars migrate from circumnuclear stellar discs, will result mainly in low initial eccentricities. First results from adaptive optics observations slightly favour the Hills scenario, but the significance is still marginal. GRAVITY will significantly enlarge the number of stars with known eccentricities, and will distinguish between the formation scenarios unambiguously (see Figure 5).

Testing general relativity in the strong field regime

The unprecedented astrometric accuracy of GRAVITY may even allow the theory of general relativity to be tested in the (so far) unexplored strong field around SMBHs. The observed orbit of a hot spot on the last stable orbit will be dominated by strong gravitational effects like gravitational lensing and redshift (Figure 4). GRAVITY observations of the flaring BH will thus directly probe spacetime in the immediate vicinity of the event horizon of the BH. The stellar orbits will be notably affected by higher order general relativistic effects, for example the relativistic periastron shift and the Lense–Thirring precession of the orbital angular momentum around the BH spin axis (Figure 6). These effects will be strongest for stars within the central light-week, which will be observed with GRAVITY in its interferometric imaging mode. In the most optimistic case, GRAVITY may even be able to test the so-called "no-hair" theorem (Will, 2008), which states that a BH is fully characterised by its mass and spin. In particular the BH spin and its quadrupole moment should be strictly related. Since spin and quadrupole moment couple differently to the inclination of stellar orbits, they can be measured independently (see Figure 6).

Active galactic nuclei

The standard unified model for active galactic nuclei postulates that an accreting SMBH is surrounded by an obscuring torus, whose orientation determines if the central engine is hidden

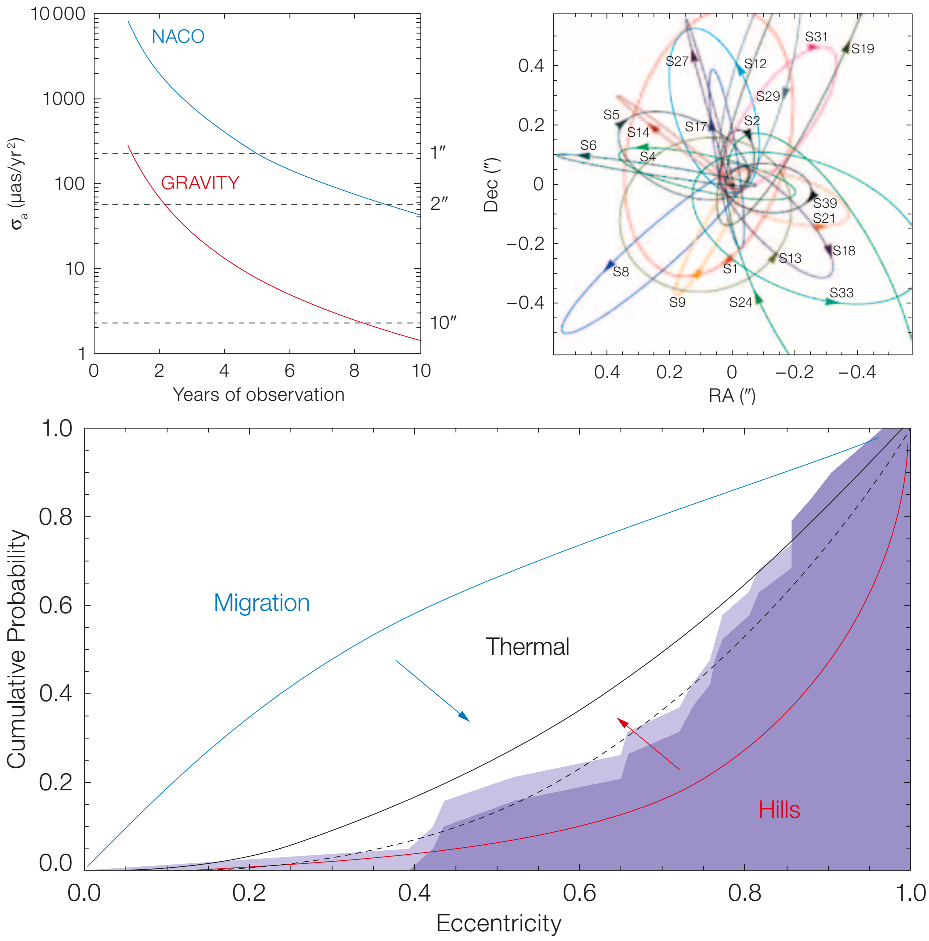


Figure 5. Solving the Paradox of Youth of the Galactic Centre stars. GRAVITY will be able to measure accelerations, i.e. individual orbits, out to about 10 arcseconds distance from the SMBH (upper left) and will significantly enlarge the number of S-stars (upper right) with precise eccentricities (from Gillessen et al., 2009). The improved eccentricity distribution (lower) can distinguish between the various formation scenarios proposed for stars in the central light-month.

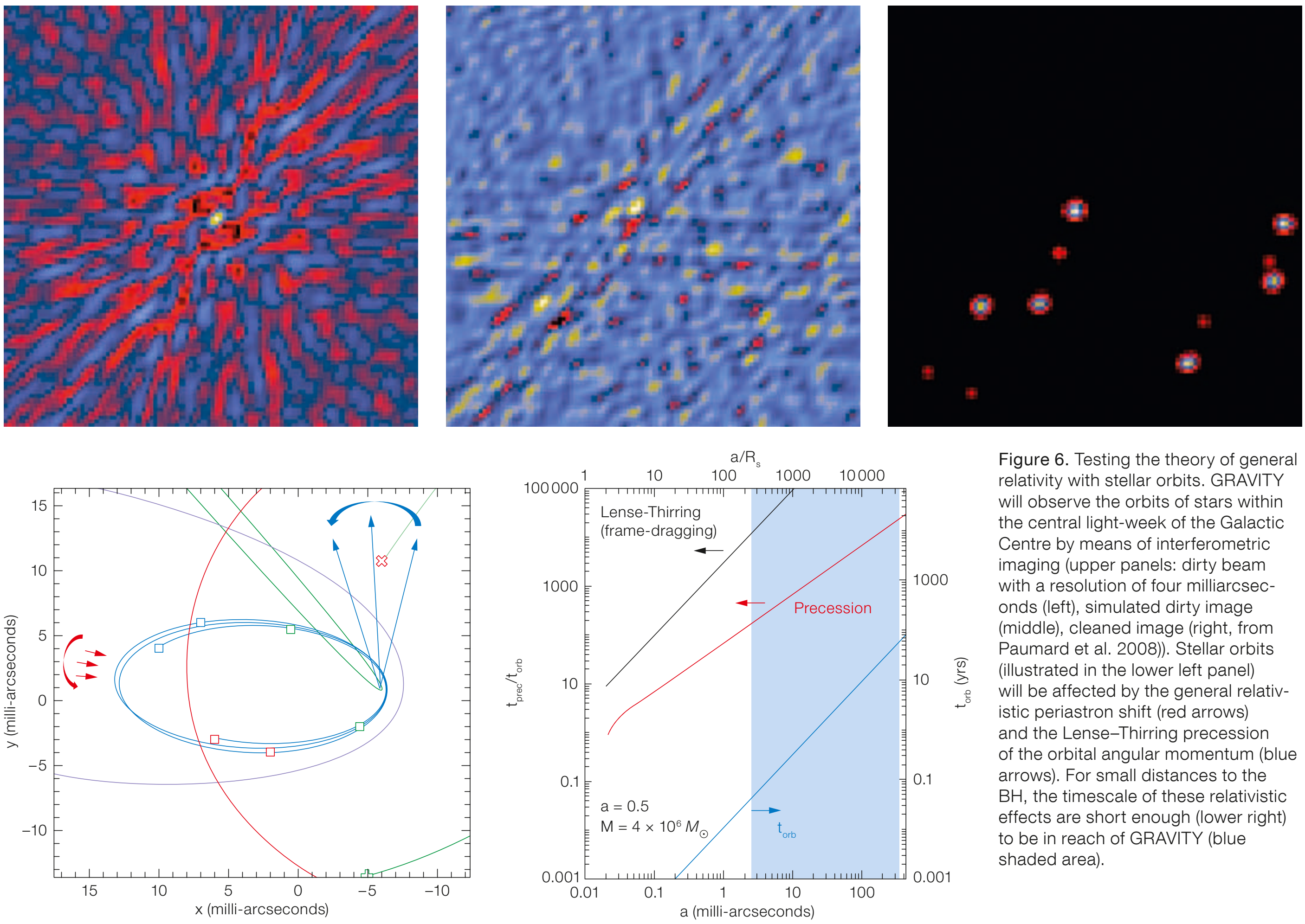


Figure 6. Testing the theory of general relativity with stellar orbits. GRAVITY will observe the orbits of stars within the central light-week of the Galactic Centre by means of interferometric imaging (upper panels: dirty beam with a resolution of four milliarcseconds (left), simulated dirty image (middle), cleaned image (right, from Paumard et al. 2008)). Stellar orbits (illustrated in the lower left panel) will be affected by the general relativistic periastron shift (red arrows) and the Lense–Thirring precession of the orbital angular momentum (blue arrows). For small distances to the BH, the timescale of these relativistic effects are short enough (lower right) to be in reach of GRAVITY (blue shaded area).

from the observer's view or not. The direct proof that this absorber is really a torus, rather than another structure, is still pending. Indeed most resolved gaseous structures on the putative scale of the torus appear more disc-like, for example the maser disc, the radio continuum emission and the mid-IR emission of the prototypical active galactic nuclei NGC 1068 (see Figure 7). Observing six baselines simultaneously, GRAVITY will image the inner edge of the torus with unprecedented quality, where the dust is close to the sublimation limit. GRAVITY will thus put strong constraints on the absorber models. These models are very much inspired by the observations of NGC 1068, but the few active galactic nuclei with interferometric observations show a puzzling variance. GRAVITY will significantly extend the sample to finally draw statistically sound conclusions.

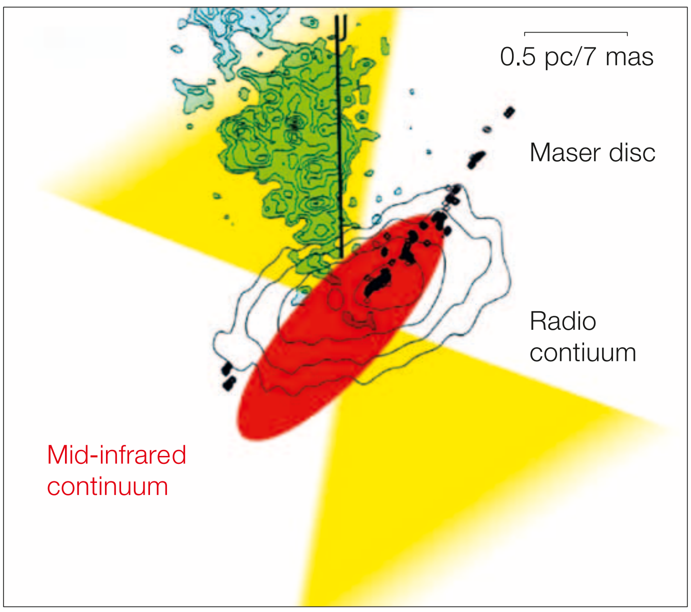
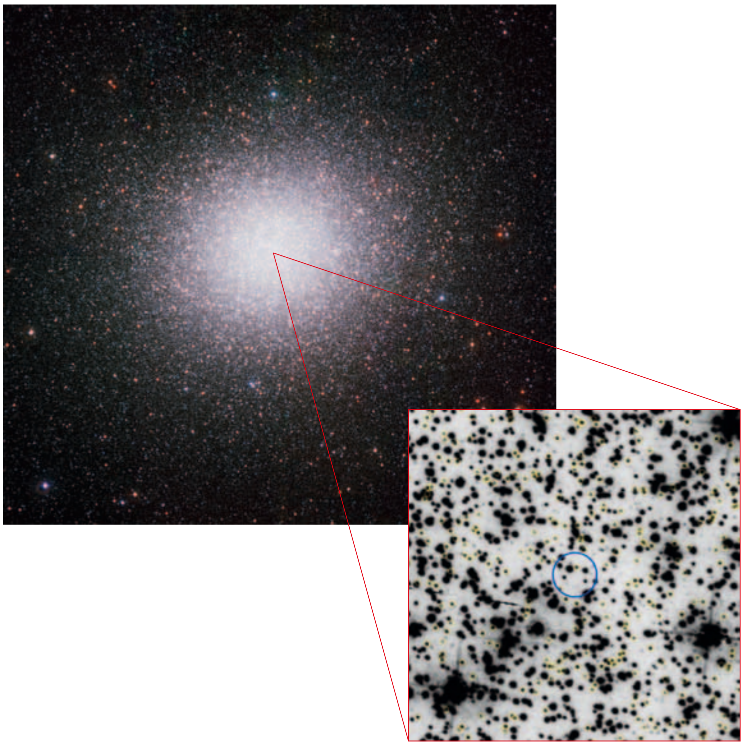


Figure 7. A sketch of the prototypical active galactic nucleus of NGC 1068 (from Raban et al., 2009). The gaseous structures and dust emission on the scale of the putative torus appear disc-like, while the unified model suggests a geometrically thick torus. Observing at NIR wavelengths, GRAVITY will image the inner edge of the absorber, putting strong constraints on the absorber geometry.



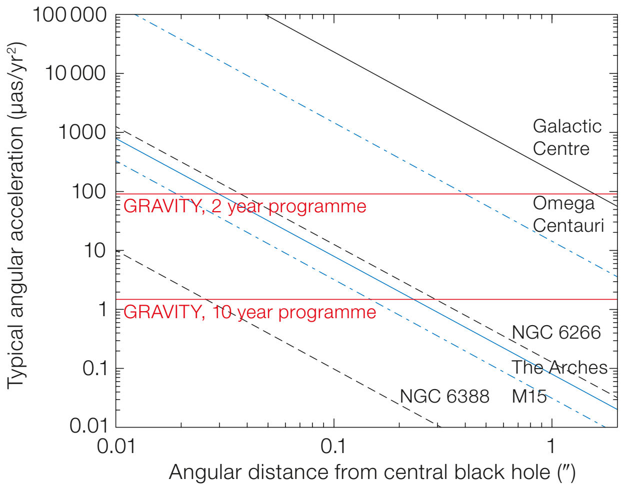


Figure 8. Discovering IMBHs in star clusters. The left panel shows the globular cluster ω Cen and a zoom into its centre (from Anderson et al., 2010). The blue circle has a radius of 1 arcsecond. The statistical analysis of the velocity dispersion is limited by having only a few stars within the sphere of influence of the BH. GRAVITY will make a clear-cut case in a few suitable clusters by measuring the accelerations of individual stars (right), directly probing the central gravitational potential.

Even the broad-line region may come in reach for GRAVITY. It is seen in those active galactic nuclei for which we have a direct view onto the SMBH. The size of the broad-line region can currently only be measured indirectly, looking at the time delay between the variations of the ultraviolet continuum and the emission lines. Broad-line regions of nearby active galactic nuclei are typically smaller than 0.1 milliarcseconds, and thus too small to be resolved in GRAVITY's images. But the astrometric accuracy of GRAVITY will allow measurement of the velocity gradient across it. This will strongly constrain the broad-line region geometry and determine dynamically the mass of the central BH.

Intermediate mass black holes

The tight correlation between the bulge mass of a galaxy and the mass of the central SMBH suggests that the rapid formation of a spheroidal stellar system also collects up to about 1 % of the initial mass in a central BH. Such a core collapse and collisional build-up may have also led to the formation of intermediate mass BHs in massive, dense star clusters. Recent searches in globular clusters show evidence for such IMBHs (Figure 8). However, the sphere of influence of the postulated BHs is typically less than a few arcseconds, such that only a few stars are available for these statistical studies. GRAVITY will dramatically change this situation in a few suitable cases for which accelerations can be detected, thus directly probing the gravitational potential without suffering from the small number statistics of velocity dispersion measurements.

X-ray binaries

X-ray binaries are the best place to study neutron stars and BHs. These neutron stars and BHs are very faint when isolated, but they can be observed as part of a X-ray binary, some of which are bright enough for GRAVITY. We expect that it will be possible to detect the orbital displacement from the compact companion in the interferometric closure phase. Even the absolute astrometric displacement of the binary system's photo-centre will be observable with GRAVITY in a few nearby systems, for which a suitable astrometric reference star is available. Combined with spectroscopy, these observations will provide the orbital elements and distance of the system, as well as the mass of the two components. In addition GRAVITY will characterise the wind from the stellar companion at a scale of a few stellar radii. The physical properties of this wind are particularly interesting as it is the main source for feeding the compact object.

Masses of the most massive stars and brown dwarfs

There is still a discrepancy of up to a factor of two in the mass estimates for the most massive main sequence stars. It is not known what the maximum allowed mass for a star is. Comparison of spectra with atmospheric models yields upper mass limits of typically 60 $M_{\odot}$, whereas evolutionary tracks and observed luminosities suggest a mass of up to 120 $M_{\odot}$. Clearly, dynamical mass estimates are required. Quite a number of spectroscopic binary O-stars are known in the cores of starburst clusters like Arches, 30 Doradus and the Galactic Centre. GRAVITY will resolve some of the longer period spectroscopic binaries, and will monitor the astrometric motions of the photo-centres for the short period, close binaries. In this way, GRAVITY will directly yield dynamical mass estimates for many of these systems, and finally provide the crucial input required to calibrate stellar evolutionary tracks.

The situation is similar for brown dwarfs, which are the lowest mass stars. Most current mass estimates are based on evolutionary models and model atmospheres, which have not yet been accurately calibrated by observations. Dynamical masses for brown dwarfs have only been derived for a few objects. In general, the observed masses for sub-stellar objects with ages older than a few 100 million years seem to be in good agreement with theoretical models. But there are significant uncertainties and discrepancies for the very young, very low mass objects like AB Dor C. If indeed these objects are more massive than indicated by stellar evolutionary models, many putative planets would be rather in the brown dwarf than the planetary mass regime. GRAVITY will probe many more multiple systems like AB Dor C, deriving the individual component masses, and even probe the sub-stellar companions themselves for binarity, thus clarifying this situation.

Jet formation in young stars

Jets are omnipresent in the Universe, from gamma-ray bursts to active galactic nuclei, from young stars to microquasars. Understanding the formation of jets is still one of the "big" open challenges of modern astrophysics. It is now known that jets are powered by magneto-hydrodynamic engines, tapping the energy of the accretion disc. Young stars are ideal objects to study these processes at the highest resolution. Matter from the disc surface couples to the open, highly inclined star–disc magnetic field lines, and is accelerated up to the Alfvén surface. The rotating magnetic field lines then become more and more twisted, wind up and collimate the jet. But surprisingly, some stellar jets are found only on one side of the disc. Clearly, some basic ingredient is missing in our understanding of jet formation. The relevant processes take place within about one astronomical unit from the star, which at the typical distance to the nearest star-forming regions of about 150 pc translates into an angular size of about 6 milliarcseconds, slightly larger than GRAVITY's 4-milliarcsecond angular resolution. By repeatedly imaging the time-dependent ejection just outside the engine at high spectral resolution, GRAVITY will provide key observational tests of time-dependent jet simulations (Figure 9). Furthermore, the astrometric signal across the emission line will directly probe the central engine on the sub-milliarcsecond scale, i.e. well within one astronomical unit.

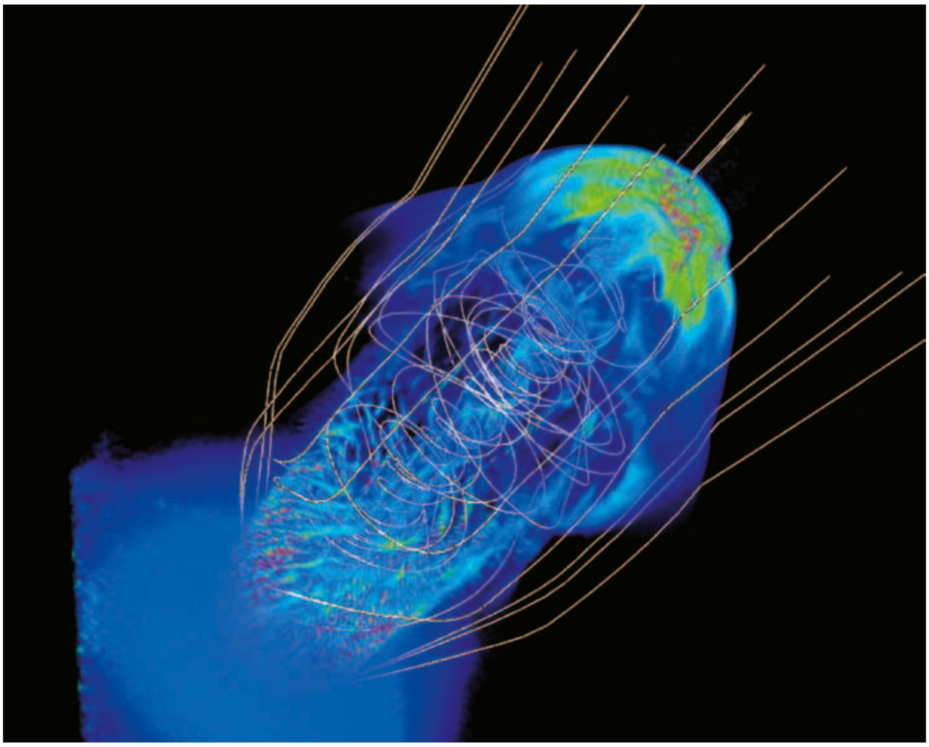


Figure 9. 3D simulation of a large-scale jet from a nearby young star. In this picture the bow shock has propagated roughly 400 milliarcseconds out from the jet engine (from Staff et al., 2010).

Planet formation in circumstellar discs

Circumstellar discs are the cradles of planet formation. Planets are thought to form rapidly in a few million years through the fast evolution of the disc structure. Dust processing, settling and coalescence are accompanied by an increase of particle size, leading to the formation of planetesimals that eventually aggregate to form planetary systems. The planet formation process is expected to leave strong imprints in the disc structure, such as inner disc clearing, gap opening and tidally induced spiral structures. GRAVITY will hunt down all these signs. Its unique sensitivity in the NIR will allow the sample of observed young stars to be increased towards the poorly explored solar-mass regime. This will be done at sub-astronomical unit resolutions for the closest star-forming regions. It will reveal the disc structure evolution, the so-called transitional step, search for disc disruption signatures, and be used to probe the presence of hot, young substellar and planetary companions.

Astrometric planet detection

Many hundreds of exoplanets have been detected to date, mostly from radial

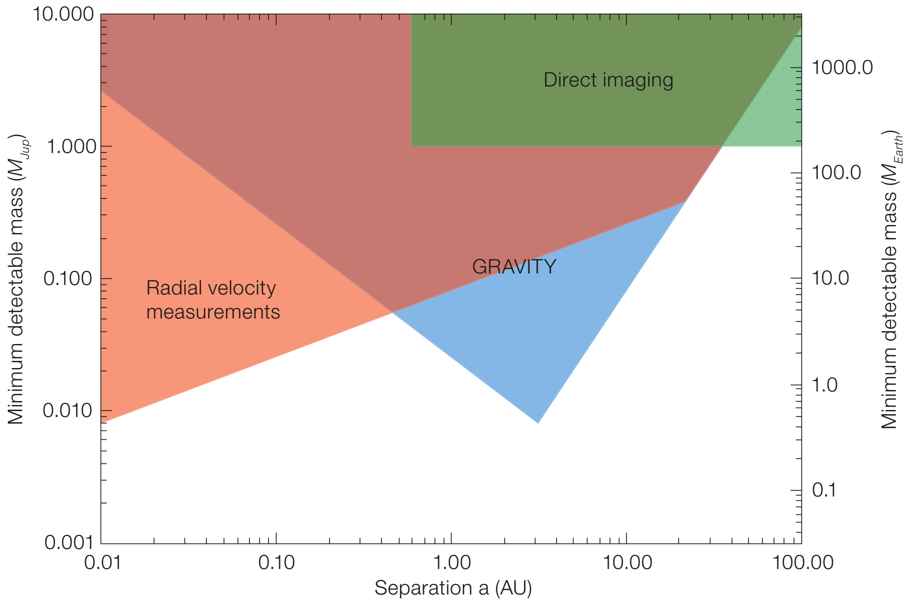


Figure 10. The realm of GRAVITY exoplanet search among very low-mass stars is shown. The blue shaded area depicts the discovery space of GRAVITY for planets around a late M dwarf at a distance of 6 pc. The green and red areas indicate roughly the parameter space probed by radial velocity observations and direct imaging.

velocity measurements and photometric transit observations. However, these methods are biased towards detecting massive planets in close orbits. Moreover, radial velocity measurements alone cannot provide the inclination of the orbit, and can thus only give a lower limit for the mass of the planet. In contrast, the reflex motion of a star observed by astrometry allows the orbital solution to be retrieved, resulting in an unambiguous measurement of the mass of the planet.

Astrometric planet detection is also a scientific goal of the PRIMA facility, currently being commissioned at the VLTI (Delplancke, 2009). While planet searches with PRIMA mostly target isolated stars or wide binaries, GRAVITY will focus on detecting brown dwarfs and exoplanets in close binary systems. For Sun-like stars, GRAVITY's survey volume would extend out to more than 200 pc. Even the much fainter M-stars, with just 20 % of the mass of the Sun, can be observed out to about 25 pc (Figure 10). GRAVITY has the potential to detect exoplanets as small as three Earth masses around an M5V star at a distance of 5 pc, or less than two Neptune masses around an M3V star at a distance 25 pc.

Transiting exoplanets

The transit of a planet in front of its host star causes an apparent motion of the photo-centre of the star and introduces a slight asymmetry in the image of the star. The former effect can be measured using GRAVITY's astrometric observing mode, the latter effect can be seen in the closure phases of the interferograms (van Belle, 2006). GRAVITY observations of such transits have the potential to measure the radius of the planet and its parent star.

For a star like HD 189733, a 0.8 $M_{\odot}$ star at a distance of about 20 pc, and its Jupiter-sized planet on a very close, two-day orbit, the apparent motion is about 10 microarceconds. This is at the limit of GRAVITY's capability, but transiting planets around later-type dwarfs would be easier to detect. This type of measurement will also give the position angle of the orbit on the sky, which, combined with the direction and amount of polarisation of the light reflected by the planet, might ultimately even place constraints on the distribution of surface features like clouds and weather zones.

On sky in 2014

The GRAVITY project emerged from ESO's second generation VLTI instrument workshop in 2005. Following the initial Phase A study in 2006/7, ESO's Science and Technical Committee's recommendation and ESO Council's endorsement in 2008, and the preliminary design review in 2010, the project is currently in its final design phase. First astronomical light at the VLTI is planned for 2014.

References

Amorim, A. et al. 2010, Proc. SPIE, 7734, 773415
Anderson, J. et al. 2010, ApJ, 710, 1032
Bartko, H. et al. 2010, Proc. SPIE, 7734, 773421
van Belle, G. 2008, PASP, 120, 617
Choquet, E. et al. 2010, Proc. SPIE, 7734, 77341Z
Clénet, Y. et al. 2010, Proc. SPIE, 7736, 77364A
Delplancke, F. 2008, NewAR, 52, 199
Eckart, A. et al. 2010, Proc. SPIE, 7734, 77340X
Eisenhauer, F. et al. 2008, *The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation Instrumentation,* ed. Richichi, A. et al., ESO Astrophysics Symposia, 41, 431
Genzel, R. et al. 2010, RvMP, 82, 3121
Gillessen, S. et al. 2010, Proc. SPIE, 7734, 77340Y
Gillessen, S. et al. 2009, ApJ, 692, 1075
Jocou, L. et al. 2010, Proc. SPIE, 7734, 773430
Paumard, T. et al. 2008, *The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation Instrumentation,* ed. Richichi, A. et al., ESO Astrophysics Symposia, 41, 431
Pfuhl, O. et al. 2010, Proc. SPIE, 7734, 77342A
Raban, S. et al. 2009, MNRAS, 394, 1325
Staff, J. E. et al. 2010, ApJS, 722, 1325
Straubmeier, C. et al. 2010, Proc. SPIE, 7734, 773432
Will, C. M. 2008, ApJL, 674, 25