GRAVITY: Observing the Universe in Motion

- Ten year large program
- Three year program
- Single season campaign

- Orbit of exo-Jupiter/Uranus
- Detection of intermediate mass BH in GCs/Arches
- Detection of SR/GR effects in cusp star orbits
- Detection of ‘dark halo’ around SgrA*
- Astrometric signal exo-Jupiter/Uranus
- Evolution outflows in YSOs & micro-QSOs
- Proper motions massive star cluster
- Imaging jets/disks in YSOs & CBs
- Binary dynamics
- Lensing
- Stellar motions in nuclei of nearby galaxies
- Gas flows in AGN
- 3D dynamics of nuclear star cluster

Maximum distance from Earth (pc)
GRAVITY: Observing the Universe in Motion

The Messenger

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GRAVITY is the second generation Very Large Telescope interferometer instrument for precision narrow-angle astrometry and interferometric imaging. With its fiber-fed integrated optics, wavefront sensors, fringe tracker, beam stabilization and a novel metrology concept, GRAVITY will push the conciseness 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 jet formation in young stellar objects, 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 scales in astrophysics

Much as long-baseline radio interferometry has been, 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 high-angle interpretation of the near-infrared (NIR) flares is correct, GRAVITY has the potential to directly determine the accretion rate and mass accretion histories of individual stars close to the BH. GRAVITY will also 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
Setting the Scale – just to scare …

6 $R_S$

$R_S \sim 10 \mu\text{as}$

1 Schwarzschild radius = a coin on the moon

Earth Orbit
Phase Referenced Imaging & Astrometry

$$\delta OPD = \vec{B} \cdot \vec{\alpha} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{\alpha} - \vec{\beta})$$

Secondary Star

Primary Star

$\Delta \delta < 60$ arcsec

OPD(t)

OPD(t)

$B$

GC

2"

[Image of a diagram showing phase referenced imaging and astrometry concepts with mathematical formula and star diagrams]
Phase Referenced Imaging & Astrometry

Contrast (B) <-> Fourier Transform (Image)

Secondary Star  Primary Star

\[ \Delta s < 60 \text{ arcsec} \]

OPD(t)

2" GC

OPD(t) \( B \)
Adaptive Optics

Interferometric Beam

Light from telescope

Wavefront-Sensor

PRIMA Star Separator

Brander, Hippler et al., Clenet et al. 2010
Adaptive Optics and Fringe Tracking Detectors

SELEX / ESO development of Infrared Avalanche Photo Diode array:

Finger et al. 2010

Brander, Hippler et al., Clenet et al. 2010
Beam Combiner Instrument

- Acqiuision Camera
- Spectrometers
- Guiding system
- Fiber Couplers
- Fiber Control Unit
- Metrology Injection Units
- Integrated Optics Beam Combiners

Haug, Thiel et al.
Fluoride glass fibers (OHANA)
• optimum throughput in K-band
• possibility to measure in unpolarized light = sensitivity

Perrin, Perraut, Jacou et al.
Fiber control

Perrin et al.
Integrated Optics

Optical equivalent of electronic integrated circuits

Jacou et al. 2010, Perraut et al.
Integrated Optics

K-band operation

Average throughput: 59%

PECVD
FHD

Cryogenic operation

Jacou et al.
2010,
Perraut et al.
Spectrometers

Collimator

Metrology Laser Injection

Grism wheel

IO Beam combiner

Camera

Dichroic + Blocking Filter

Wollaston

Detector Focus Stage

Straubmeier et al. 2010
Menu, Choquet, Fedou, Dembet, et al.
Fringe Tracker

Choquet et al. 2010

Fringetracking testbed @ LESIA

Lab data

OPD (μm)

Time (ms)
Narrow Angle Astrometry

\[ \delta \text{OPD} = \vec{B} \cdot \vec{a} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{a} - \vec{\beta}) \]
Interferometric Astrometry

\[ \delta \text{OPD} = \vec{B} \cdot \vec{\alpha} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{\alpha} - \vec{\beta}) \]

5 nm

500 µm  10 µas
Interferometric Baseline

\[ \delta \text{OPD} = \mathbf{B} \cdot \hat{\alpha} - \mathbf{B} \cdot \hat{\beta} = \mathbf{B} \cdot (\hat{\alpha} - \hat{\beta}) \]

- Pivot point
- Phase reference of the metrology
- Narrow angle baseline
- Wide angle baseline
- Imaging baseline

Lacour et al.
Interferometric Baseline

\[ \delta OPD = \mathbf{B} \cdot \mathbf{\alpha} - \mathbf{B} \cdot \mathbf{\beta} = \mathbf{B} \cdot (\mathbf{\alpha} - \mathbf{\beta}) \]
Narrow Angle Baseline

Stable realization of the narrow angle baseline

\[ \delta OPD = \vec{B} \cdot \vec{\alpha} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{\alpha} - \vec{\beta}) \]

500 µm

Calibration of the narrow angle baseline

Lacour, Kervella et al.
Interferometric Astrometry

\[ \delta \text{OPD} = \vec{B} \cdot \vec{\alpha} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{\alpha} - \vec{\beta}) \]

**OPD measurement Error**
- Phase error on SC target
- Phase error on FT target
- Wavelength error

**Metrology Error**
- Phase measurement error
- Metrology wavelength stability

**Baseline Error**
- Short term stability?
- Long term stability?

**Goal:** \( 10 \mu\text{as} \times \sqrt{3} \) in 5 minutes

**Dispersive Error**
- Hysteresis of the fibered delay lines
- Refractive index of air
- Refractive index of fluoride glass

**Pupil positioning Error**
- Tip-tilt error
- Lateral pupil error
- Longitudinal pupil error

Lacour et al.
Pupil Errors

For perfect tip-tilt correction

For simultaneous tilt error
Interferometric Astrometry

\[
\begin{align*}
\frac{1}{2} (\Delta \alpha_1 + \Delta \beta_1) \cdot & (\text{pup}_{\text{FT1}} - \text{pup}_{\text{SC1}}) \\
\frac{1}{2} (\Delta \alpha_1 - \Delta \beta_1) \cdot & (\text{pup}_{\text{FT1}} + \text{pup}_{\text{SC1}} - 2\text{pup}_{\text{M1}}) \\
\frac{1}{2} (\Delta \alpha_2 + \Delta \beta_2) \cdot & (\text{pup}_{\text{FT2}} - \text{pup}_{\text{SC2}}) \\
\frac{1}{2} (\Delta \alpha_2 - \Delta \beta_2) \cdot & (\text{pup}_{\text{FT2}} + \text{pup}_{\text{SC2}} - 2\text{pup}_{\text{M2}})
\end{align*}
\]

FT/SC differential pupil error

Lateral pupil error

Lacour et al.
Align your fibers (angles) well, and actuate both pupils with the same actuator.
- Telescope pointing error / common tip/tilt does not hurt too much.

Acquire well, and actuate tip/tilt of both fibers.
- Pupil error does not hurt too much.

Control pupil such that fiber pupils are fixed on metrology reference.

Minimize Tip/Tilt and guiding errors.

Lacour et al.
Tilt Control

Atmosphere   VLTI Tunnel

Pfuhl et al., Amorim et al. 2010,
Pupil Control

No shifts at 45° pupil rotation

Amorim et al. 2010, Pfuhl et al.
Fibercoupler

Tip-Tilt-Piston-Actuator

Pupil-Actuator

Pfuhl et al. 2010

Rotation Stages

Shutters

X,Y,Z Stages
Laser Metrology

$$\delta OPD = \vec{B} \cdot \vec{\alpha} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{\alpha} - \vec{\beta})$$

Rabien et al. 2008, Bartko et al. 2010, Gillessen et al.
GRAVITY Key Figures

Fringe Tracking:
• UTs: K~10 mag
• ATs: K~7 mag

Milestones:
• Final design in 2011/12
• Installation at the telescope in 2014

Astrometry:
• few 10 μas in 5 minutes

Interferometric Imaging:
• UTs: K~16, ATs: K~13 in 100s
• SNR(V) = 10 for visibility
• $\sigma(\phi) = 0.1 \text{ rad for referenced phase}$
Thank you very much for your attention