Detecting relativistic effects on the orbit of the S2 star with GRAVITY

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Guy Perrin, Thibaut Paumard & Frédéric Vincent

The Multi-Messenger Astrophysics of the Galactic Centre
July 18th 2016
Outline

The GRAVITY instrument

Major scientific goals of GRAVITY

First GRAVITY observations

Theoretical study: detection of relativistic effects with the S2 star and GRAVITY
Interferometer (4 telescopes)  
*(Eisenhauer+11)*

- installed during the summer 2015 at VLT  
- near-infrared  
- VLT FOV = 2''  
- astrometry in a scientific FOV = 60 mas

The GRAVITY instrument

VLT FOV = 2''

Reference Star

θ

Scientific object

sc. FOV = 60 mas
The GRAVITY instrument

1. Optical path difference

2. Fringe Tracker + Delay lines

3. Beam combiner

Reference Star
Scientific object

Adaptative Optics
The GRAVITY instrument

Reference Star

Scientific object

Adaptative Optics

Fringe Tracker + Delay lines

Beam combiner

1. Optical path difference

2. Beam combiner

3. I(0°) → A
   I(90°) → B
   I(180°) → C
   I(270°) → D

5/21
The GRAVITY instrument

σ(θ) = 10 μas

Reference Star

Scientific object

Barcelona

Paris
Major scientific goals of GRAVITY

Observe the Galactic Center:

- detect relativistic effects with a high accuracy
- constrain the nature of the object located at the Galactic center
- constrain the nature of flares detected close to the central source

S cluster → S2 star

\[ M_0 \approx 4.31 \pm 0.6 \times 10^6 M_\odot \]

Ghez+08, Gillessen+09

Apparent size:

\[ \Theta \approx 53 \, \mu \text{as} \]

Biggest apparent black hole
Major scientific goals of GRAVITY

Observe the Galactic Center:

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Light curve of Sgr A*:

$\Delta t \approx 1$ hr

Jet model  Hot spot model  Red noise model

Yusef-Zadeh+12
First GRAVITY observations

Observation of the S2 star and IRS 16C (reference star for the Galactic Center)

→ determine whether these stars are not binary stars

Both stars are not binary stars

Preliminary analysis from Pfuhl, Perrin +
First GRAVITY observations

Observation of the binary star G2V + G6III

→ measure the angular separation between the two stars
→ first step in accurate astrometry

\[ \mu \text{ Vel} \]

2279 mas

One night of observation

Statistical error 14 µas

Several nights of observation

Systematic error 140 µas in DEC

Systematic error 40 µas in RA

Preliminary analysis Pfuhl, Kervella, Woillez +
Theoretical study: detection of relativistic effects with the S2 star

Estimate the minimal observation times needed for GRAVITY to detect relativistic effects with the S2 star.

Determine whether GRAVITY could constrain the spin of the hypothetical black hole with S2.
Special relativity:
(TD) transverse Doppler effect

General relativity:
- effects on the star trajectory
  (PA) pericenter advance
  (LTS) Lense-Thirring
- effects on the photon trajectory
  (LTP) Lense-Thirring
  (GR) gravitational redshift
  (GL) gravitational lensing

<table>
<thead>
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<th>Spectro. (km/s)</th>
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Effects: [1.7 km/s, 3.4 km/s]
Pericenter: 0.8 mas
Apocenter: 1.4 mas

17 km/s
34 km/s
Theoretical study: detection of relativistic effects with the S2 star

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<td>40</td>
<td>1</td>
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<td>(LTP)</td>
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Black hole does not rotate

Black hole rotates

Spin = 0.99, $\Omega' = 20^\circ$, $i' = 135^\circ$
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<tr>
<td>(GR)</td>
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<td>100</td>
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<tr>
<td>(GL)</td>
<td>20</td>
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Diagram showing the primary and secondary images of the S2 star with pericenter and apocenter markers.
Observations generated with the D model

Stellar-orbit models

<table>
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Theoretical study: detection of relativistic effects with the S2 star

Fit the A, B and C models to observations generated with the D model and determine when these models fail to describe the observations.
Theoretical study: detection of relativistic effects with the S2 star

### Minimal observation times needed to detect relativistic effects

<table>
<thead>
<tr>
<th>Detected Effects</th>
<th>A</th>
<th>10 µas</th>
<th>30 µas</th>
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<tbody>
<tr>
<td>(TD) (GR)</td>
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<tr>
<td>1 km/s</td>
<td>1 month</td>
<td>1 month</td>
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<tr>
<td>10 km/s</td>
<td>2 months</td>
<td>2 months</td>
<td></td>
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<tr>
<td>(PA) (GL)</td>
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<tr>
<td>1 km/s</td>
<td>4 months</td>
<td>10 years</td>
<td></td>
</tr>
<tr>
<td>10 km/s</td>
<td>6 years</td>
<td>18 years</td>
<td></td>
</tr>
<tr>
<td>(GL)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 km/s</td>
<td>6 months</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>10 km/s</td>
<td>6 years</td>
<td>&gt; 30 years</td>
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Can we constrain the spin of the black hole with GRAVITY and S2?

→ use a C+ model including lensing effects: analytical formulas from Sereno+06

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<tr>
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<th>B</th>
<th>C</th>
<th>C+</th>
<th>D</th>
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<td>(TD)</td>
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Preliminary results for (10µas, 10km/s) and 3 periods of S2:

- \( spin \approx 0.95 \pm 0.13 \)
- \( \Omega' \approx 63.7 \pm 29.1 \degree \)
- \( i' \approx 138.1 \pm 15.7 \degree \)
Summary

GRAVITY observations:

1) S2 and IRS 16C are not binary stars
2) Astrometric accuracy of about 10 µas reached for one night of observation
3) Next steps:
   - finish the commissioning for fall 2016
   - prove that the astrometric accuracy of 10 µas can be reached at the Galactic Center

Theoretical study:

1) Detections with GRAVITY and the S2 star of:
   - transverse Doppler and gravitational redshifts in few months
   - gravitational lensing in ≈ 4-6 months for (10µas, 1km/s) or ≈ 6 years for (10µas, 10km/s)
   - pericenter advance in ≈ 10 years for (30µas, 1km/s) or ≈ 20 years for (30µas, 10km/s)

2) Seems that we can constrain the spin parameter with S2 and without ray-tracing code, but we need long monitoring