Gamma Astrometric Measurement Experiment

M. Gai - INAF-Osservatorio Astronomico di Torino

On some goals of Fundamental Physics achievable through astronomical techniques...
GAME:  
Gamma Astrometric Measurement Experiment

Space-time curvature parameter $\gamma$

Apparent star position variation

Light deflection close to the Sun

Space mission

Approach:

build on flight inheritance from past missions

[SOHO, STEREO, Hipparcos, Gaia]
Outline of talk:

• **Scientific rationale**

• The GAME implementation concept

Goal of GAME: $\gamma$ to $10^{-7}$
Scientific rationale of GAME

Goals: Fundamental physics; cosmology; astrophysics

- The classical tests on General Relativity
- Light deflection from spacetime curvature
- The Dyson - Eddington - Davidson experiment (1919)
- Current experimental findings on $\gamma$
- Cosmological implications of $\gamma$
- Science bonus: additional topics
Classical tests of general relativity [Einstein, 1916]

1. Perihelion precession of planetary orbit ⇒ Mercury
2. Light deflection by massive objects (Sun) ⇒ Eddington’s parameter $\gamma$
3. Gravitational redshift / blueshift of light

“Modern” tests:
- Gravitational lensing; Equivalence principle;
- Time delay of electromagnetic waves (Shapiro effect);
- Frame dragging tests (Lense-Thirring effect);
- Gravitational waves; Cosmological tests (cosmic background)
Scientific rationale of GAME

Goals: Fundamental physics; cosmology; astrophysics

• The classical tests on General Relativity

  • _Light deflection from spacetime curvature_

  • The Dyson - Eddington - Davidson experiment (1919)

• Current experimental findings on \( \gamma \)

• Cosmological implications of \( \gamma \)

• Science bonus: additional topics
Spacetime curvature around massive objects

\[ \delta \psi = (1 + \gamma) \frac{GM}{c^2 d} \sqrt{\frac{1 + \cos \psi}{1 - \cos \psi}} \]

1'' .74 at Solar limb \( \cong 8.4 \, \mu \text{rad} \)

G: Newton’s gravitational constant
\( d \): distance Sun-observer
M: solar mass
\( c \): speed of light
\( \psi \): angular distance of the source to the Sun

Light deflection \( \Leftrightarrow \) Apparent variation of star position, related to the gravitational field of the Sun
\( \Leftrightarrow \gamma \) in Parametrised Post-Newtonian (PPN) formulation
Scientific rationale of GAME

Goals: Fundamental physics; cosmology; astrophysics

• The classical tests on General Relativity
• Light deflection from spacetime curvature
• *The Dyson - Eddington - Davidson experiment (1919)*
• Current experimental findings on $\gamma$
• Cosmological implications of $\gamma$
• Science bonus: additional topics
Dyson-Eddington-Davidson experiment (1919) - I

First test of General Relativity by light deflection nearby the Sun

Epoch (a): unperturbed direction of stars S1, S2 (dashed lines)

Epoch (b): apparent direction as seen by observer (dotted line)
Dyson-Eddington-Davidson experiment (1919) - II

Repeated throughout XX century

Precision achieved: ~10%

[A. Vecchiato et al., MGM 11 2006]

Limiting factors:

- Need for natural eclipses ➔ Short exposures, high background
- Atmospheric turbulence ➔ Large astrometric noise
- Portable instruments ➔ Limited resolution, collecting area

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Deflection [&quot;]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyson &amp; al.</td>
<td>1920</td>
<td>1.98 ± 0.16</td>
</tr>
<tr>
<td>Dodwell &amp; al.</td>
<td>1922</td>
<td>1.77 ± 0.40</td>
</tr>
<tr>
<td>Freundlich &amp; al.</td>
<td>1929</td>
<td>2.24 ± 0.10</td>
</tr>
<tr>
<td>Mikhailov</td>
<td>1936</td>
<td>2.73 ± 0.31</td>
</tr>
<tr>
<td>van Biesbroeck</td>
<td>1947</td>
<td>2.01 ± 0.27</td>
</tr>
<tr>
<td>van Biesbroeck</td>
<td>1952</td>
<td>1.70 ± 0.10</td>
</tr>
<tr>
<td>Schmedidler</td>
<td>1959</td>
<td>2.17 ± 0.34</td>
</tr>
<tr>
<td>Schmedidler</td>
<td>1961</td>
<td>1.98 ± 0.46</td>
</tr>
<tr>
<td>TMET</td>
<td>1973</td>
<td>1.66 ± 0.19</td>
</tr>
</tbody>
</table>
Scientific rationale of GAME

Goals: Fundamental physics; cosmology; astrophysics

• The classical tests on General Relativity
• Light deflection from spacetime curvature
• The Dyson - Eddington - Davidson experiment (1919)

• Current experimental findings on $\gamma$
• Cosmological implications of $\gamma$
• Science bonus: additional topics
Current experimental results on γ…

**Hipparcos**

Different observing conditions: *global astrometry*, estimate of full sky deflection on survey sample

Precision achieved: 3e-3

**Cassini**

Radio link delay timing, $\delta \nu/\nu \sim 1e^{-14}$

(similarly for Viking, VLBI: Shapiro delay effect, “temporal” component)

[B. Bertotti et al., Nature 2003]

Precision achieved: 2e-5
Scientific rationale of GAME

Goals: Fundamental physics; cosmology; astrophysics

• The classical tests on General Relativity
• Light deflection from spacetime curvature
• The Dyson - Eddington - Davidson experiment (1919)
• Current experimental findings on $\gamma$
• Cosmological implications of $\gamma$
• Science bonus: additional topics
Cosmological implications

- Dark Matter and Dark Energy: explain experimental data
- Alternative explanations: modified gravity theories – e.g. $f(R)$
- Possible check: fit of gravitation theories with observations
- Check of modified gravitation theories within Solar System

Rationale:
replacement in Einstein’s field equations of
source terms [new particles] on one side with
geometry terms [curvature] on the other side
DE and DM from the Observations

- Universe evolution is characterized by different phases of expansion

![Astronomical diagram showing the phases of cosmic evolution](image)

- **Dark Matter**
- **Ordinary Matter**
- **Radiation**
- **Dark Energy**

![Astronomical diagram showing the phases of cosmic evolution](image)

- **Big Bang**
- **10 billion years ago**
- **5 billion years ago**
- **Today**

ACS discovers two distant Type Ia supernovae
Check of gravitation theories within Solar System

Taking advantage of PPN limit, e.g. for $f(R)$ theories…

$$\gamma^\text{PPN}_R - 1 = \frac{-f''(R)^2}{f'(R) + 2f''(R)^2}, \quad \beta^\text{PPN}_R - 1 = \frac{1}{4} \left[ \frac{f'(R) \cdot f''(R)}{2f'(R) + 3f''(R)^2} \cdot \frac{d\gamma^\text{PPN}_R}{d\phi} \right]$$

Alternative formulation:

$$\gamma^\text{PPN}_R - 1 = \frac{- \left( f'' \frac{dR}{d\phi} \right)^2}{Zf' + 2 \left( f'' \frac{dR}{d\phi} \right)^2}, \quad \beta^\text{PPN}_R - 1 = \frac{1}{4} \left[ \frac{f' \cdot f'' \frac{dR}{d\phi}}{2zf' + 3 \left( f'' \frac{dR}{d\phi} \right)^2} \cdot \frac{d\gamma}{dR} \cdot \frac{dR}{d\phi} \right]$$

[Capozziello & Troisi 2005]

Local measurements $\Rightarrow$ cosmological constraints
Scientific rationale of GAME

Goals: Fundamental physics; cosmology; astrophysics

- The classical tests on General Relativity
- Light deflection from spacetime curvature
- The Dyson - Eddington - Davidson experiment (1919)
- Current experimental findings on $\gamma$
- Cosmological implications of $\gamma$
- Science bonus: additional topics
Additional science topics - I

Fundamental physics experiments in the Solar System ⇔ planetary physics

Light deflection effects due to oblate and moving giant planets: Jupiter and Saturn
  • Monopole and quadrupole terms of asymmetric mass distribution

Close encounters between Jupiter and selected quasars and stars
  • Speed of gravity; link between dynamical reference system and ICRF

Mercury’s orbit monitoring
  • Perihelion precession determination ⇒ PPN β parameter
Additional science topics - II

Astrophysics of planet-star transition region

Upper limits on masses of massive planets and brown dwarfs
• Nearby (d < 30-50 pc), bright (4 < V < 9) stars, orbital radii 3-7 AU

Time resolved photometry on transiting exo-planet systems
• Constraints on additional companions: mass, period, eccentricity

[Sample not conveniently observable by Gaia or Corot]
Additional science topics - III

Monitoring of Solar corona and asteroids

Observation in / through inner part of Solar System

- NEO orbits and asteroid dynamics (a few close encounters)
- Circumsolar environment transient phenomena (high resolution corona observations)
Complementary GR tests:

measurement of $\beta$
from Mercury orbit

$2 + 2\gamma - \beta$

Same instrument $\Rightarrow$ cross-calibration
Mercury observability

~6 periods in 2 year mission lifetime (dotted line)
Orbit region accessible to GAME: <30° to Sun

Magnitude / pixel fits GAME dynamic range (scaling exposure time)
Performance assessment in progress
Outline of talk:

- Scientific rationale
- *The GAME implementation concept*

Goal of GAME: $\gamma$ to $10^{-7}$
The GAME concept (I)

A space mission in the visible range to achieve

- long permanent artificial eclipses
- no atmospheric disturbances, low noise

Observer in space with CCD technology
Experimental approach:
Repeated observation of fields close to the Ecliptic
Measurement of angular separation of stars between fields
Track separation with epoch $\Leftrightarrow$ distance to Sun
Mission profile

Sun-synchronous orbit, 1500 km elevation ⇒ no eclipse

100% nominal observing time

Stable solar power supply and thermal environment ⇒ instrument structural stability
GSCII star counts along ecliptic plane

Astrometric performance depends on actual number, brightness and spectral type of observed targets (7’ field)

“Gaps” due to
- extinction / reddening
- removal of “blended” stars

Average values
Astrometric signature at $2^\circ$ ecliptic latitude

Peak displacement between stars @ $\pm 2^\circ$: 466 mas

Largest signature restricted to an angular range of $\pm 10^\circ$ along the ecliptic, i.e. about $\pm 10$ days
Key issues of GAME

• **Observation sequence**
• Fully differential measurement
• Precision on image location
• Systematic error control: beam combiner

• **Basic technical requirements**
• The Fizeau interferometer/coronagraph
• Elementary astrometric performance
• **Photon limited mission performance**
Observation sequence

Two measurements epochs to modulate deflection on fields F1, F2

(Sun "switched" on/off)
Key issues of GAME

- Observation sequence
- **Fully differential measurement**
  - Precision on image location
  - Systematic error control: beam combiner
- Basic technical requirements
  - The Fizeau interferometer/coronagraph
  - Elementary astrometric performance
- Photon limited mission performance
Fully differential measurement (I)

Basic equations referred to stars in Fields 1, 2, 3, 4; Epochs 1, 2

\[ [\xi(F1; E1) - \xi(F2; E1)] - [\xi(F1; E2) - \xi(F2; E2)] = \delta\psi(F1, F2) + \Delta\beta(E1; E2) \]

Star separation variation: deflection \( \psi \) + instrument [base angle]

\[ [\xi(F3; E1) - \xi(F4; E1)] - [\xi(F3; E2) - \xi(F4; E2)] = \delta\psi(F3, F4) + \Delta\beta(E1; E2) \]

Calibration fields affected mainly by ADDITIVE variations

---

**Field 1**

**Field 2**

**Base Angle** \( \beta \):

hardware separation between observing directions
Fully differential measurement (II)

Optical scale variation (in each field)

Deflection between fields

Different collective effects on field images from

• instrument evolution (focal length, distortion)
• deflection (field displacement)

⇒ simple calibration of MULTIPLICATIVE terms
Key issues of GAME

• Observation sequence
• Fully differential measurement
• Precision on image location
  • Systematic error control: beam combiner
• Basic technical requirements
  • The Fizeau interferometer/coronagraph
  • Elementary astrometric performance
• Photon limited mission performance
Precision on image location

\[ \sigma = \alpha \frac{\lambda}{4\pi X \cdot \frac{1}{SNR}} \]

\( \sigma \): Standard deviation of image location
\( \lambda \): Effective \textit{wavelength} of observation
\( X \): Root Mean Square size of the \textit{aperture}

\textit{Signal to Noise Ratio} \( \Rightarrow \) photons, RON, background
\( N \): Number of photons collected

\( \alpha \geq 1 \): Instrumental factor of degradation (geometry, sampling, …)

\( \sigma \) \textit{can be a small fraction of pixel/image size}

[Gai et al., PASP 110, 1998]
Precision on image separation

Arc length defined by composition of individual locations

\[ \sigma^2(x_1 - x_2) = \sigma^2(x_1) + \sigma^2(x_2) \]

Precision related to

- ✔ Instrument resolution ⇒ Pupil size
- ✔ Source magnitude ⇒ Exposure time
- ✔ Average on # arcs ⇒ Field of view

Observing strategy
Key issues of GAME

- Observation sequence
- Fully differential measurement
- Precision on image location
- **Systematic error control: beam combiner**
- Basic technical requirements
- The Fizeau interferometer/coronagraph
- Elementary astrometric performance
- **Photon limited mission performance**
Systematic error control: beam combiner

Image displacement $\propto$ BC mirror tilt \textbf{only}: $1 \mu\text{as} \times 1 \text{m} = 5 \text{pm}$

Base angle \textbf{materialised} in \textbf{one} component / degree of freedom

\[ \text{Base angle} = 4^\circ \text{ on sky} \Rightarrow \pm 1^\circ \text{ BC mirror tilt} \]

Key issues of GAME

- Observation sequence
- Fully differential measurement
- Precision on image location
- Systematic error control: beam combiner

**Basic technical requirements**
- The Fizeau interferometer/coronagraph
- Elementary astrometric performance
- Photon limited mission performance
Basic technical requirements

Sufficient angular resolution and photometric SNR

⇒ increase telescope size

[collect more photons and concentrate them more effectively]

Sufficient rejection of high Solar (background + diffracted) flux

⇒ reduce telescope size; increase baffling

[shield line of sight from sources at narrow angle]

Additional considerations: exposure time, spectral bandwidth, …

Above all: instrument stability and/or geometric calibration

Trade-off among conflicting requirements!
Key issues of GAME

- Observation sequence
- Fully differential measurement
- Precision on image location
- Systematic error control: beam combiner
- Basic technical requirements
  - *The Fizeau interferometer/coronagraph*
  - Elementary astrometric performance
  - Photon limited mission performance
Solution: Fizeau-like interferometer + coronagraph

Goal: achieve higher resolution through small apertures

Fizeau interferometer implemented by Pupil Masking:
set of elementary apertures cut on pupil of underlying monolithic telescope \(\Rightarrow\) cophasing by alignment

Coronagraphic techniques applied to each aperture \(\Leftrightarrow\)
replication of individual coronagraphs in phased array

Geometry optimised vs. astrometry and background
Solar photons are either rejected at first surface or sent out at second one...

Apodisation
Beam distribution (II)

Pupil Mask / Occulter

Primary Mirror (M1)

North Field Beam

Sunward sub-pupil

Geometric optics representation

Photons from stars in N field separated from Sun beam at second surface...
Similarly for photons from stars in S field…

Symmetric situation for the two beams
Beam distribution (IV)

N and S stellar beams retained, Sun rejected
Beam footprint on primary mirror

Pupil map

Optics size: ~0.5×0.7 m

Front mask size: ~0.7×0.8 m

Entrance slit (solid)

Output slit (dotted)
Beam Combination (I)

N and S stellar beams folded onto telescope optical axis by beam combiner
**Beam Combination (II)**

**Requirements on Beam Combiner:**
Two flat, pierced mirrors set at fixed angle
High dimensional stability over epochs

**Proposed solution:**
Pierced prism hosting one optical surface and supporting flat mirror e.g. by silicon bonding (LISA)
Near-monolithic assembly
Overall layout

Korsch, 4 mirrors, EFL = 19.50 m, visibility > 95% over 20×20 arcmin field; distortion < 1e-4

[Loreggia et al., SPIE 2010]
Key issues of GAME

• Observation sequence
• Fully differential measurement
• Precision on image location
• Systematic error control: beam combiner
• Basic technical requirements
• The Fizeau interferometer/coronagraph
• Elementary astrometric performance
• Photon limited mission performance
Elementary astrometric performance

Bright case:
100 s exposures, close to Sun
Background: 15.5 mag per square arcsec

Faint case:
500 s exposures, away from Sun
Background: 19.5 mag per square arcsec

Precision on a 15 mag star: < 1 mas

Band: $\lambda_0 = 650$ nm, $\Delta \lambda = 120$ nm

[Gai et al., PASP 110, 1998]
Key issues of GAME

• Observation sequence
• Fully differential measurement
• Precision on image location
• Systematic error control: beam combiner
• Basic technical requirements
• The Fizeau interferometer/coronagraph
• PSF of the phased array
• Photon limited mission performance
Photon limited mission performance - I

1 million 15 mag stars required to achieve 1 µas cumulative

⇒ 2e-6 equivalent precision on γ

Observing time required: 20 + 20 days

[Gai et al., SPIE 2009]

[on average Galactic plane stellar density from GSCII]

Observation focused on Galactic centre / anti-centre region:

3e-7 equivalent precision on γ ⇔ 2 + 2 month

[Gai et al., COSPAR 2010; Vecchiato et al., COSPAR 2010]
Photon limited mission performance - II

Example:

Systematic error scaled more slowly than random noise, dominant on long periods

$$\sigma_{(sys)} \approx N^{-1/3}$$

Systematic error control crucial to fulfilment of mission goal
Concluding remarks

✓ Astronomical techniques ⇒ Fundamental Physics

✓ Differential μas-level astrometry ⇒ PPN γ to $10^{-6} – 10^{-7}$ range

✓ Efficient implementation on dedicated space mission

✓ Observation concentrated on few epochs, high density regions

✓ Instrument based on proven technologies:
    coronagraphy + Fizeau interferometry

✓ Future steps:
    ✷ formation of science consortium;
    ✷ detailed design proposal to space agencies
GAME OVER [PRESENTATION]