Exploring gravity in the strong field regime with high throughput X-ray measurements

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3. What are the fundamental physical laws of the Universe?
   3.1 Explore the limits of contemporary physics
   Use stable and weightless environment of space to search for tiny deviations from the standard model of fundamental interactions

   3.2 The gravitational wave Universe
   Make a key step toward detecting the gravitational radiation background generated at the Big Bang

   3.3 Matter under extreme conditions
   Probe gravity theory in the very strong field environment of black holes and other compact objects, and the state of matter at supra-nuclear energies in neutron stars

Does matter orbiting close to a Black Hole event horizon follow the predictions of General Relativity?
MOTION OF MATTER CLOSE TO THE EVENT HORIZON

ASTROPHYSICS NEAR BLACK HOLES: STRONG FIELD EFFECTS
- Inner Stable Circular Orbit
- Orbital motion near ISCO
- Frame dragging, light deflection, Shapiro effect

ASTROPHYSICAL IMPACT
- Black hole spins
- AGN feedback
- Relativistic jets
- Accretion physics

X-RAY DIAGNOSTICS:
- Precision measurements
- Strong field motions: orbital & epicyclic
- Fe line spectral timing
- Reverberation
- Doppler tomography

RELATIVISTIC EFFECTS ARE SMALL PERTURBATIONS

Current best tests of General Relativity: millisecond radiopulsars

VERIFY GENERAL RELATIVITY
TEST ALTERNATIVE THEORIES

PROBING SPACETIME AND MATTER UNDER EXTREME CONDITIONS
Accreting Black Holes

- Stellar mass Black Holes in X-ray binaries

- Accretion-released energy leads to powerful X-ray emission from the innermost disk regions

- X-ray flux is often very variable and spectra are complex

Supermassive Black Holes in nuclei of active Galaxies (AGN)
Line profile integrated over entire flow encodes:

- Strong field relativistic effect: Doppler shifts and boosting, gravitational redshift, strong field lensing
Fe-lines from accretion disks around supermassive black holes in AGNs

- Strong field relativistic effect: Doppler shifts and boosting, gravitational redshift, strong field lensing
- Observed in many Active Galactic Nuclei and X-ray binaries

Fe-lines probe strong field gravity (~few Rg)

E.g. MCG 6-30-15:
- Kerr BH required to fit line profile
Iron lines probe Relativity predicted velocity and redshift map

XMM + NUSTAR

Cyg X-1

AGN

Parker, Tomsick+

Parker, Matt+
Probing strong gravitational fields with Quasi Periodic Oscillations (QPOs)

Stong Field Diagnostic: Quasi Periodic Oscillations

Accreting neutron stars

Accreting black hole candidates

Sco X-1

GROJ1655−40

+ few AGN
**Strong field gravity diagnostics: Fundamental frequencies of motion**

**Frequencies of motion in strong gravity**

- Epicyclic Resonance (fixed r)
- Relativistic Precession: nodal and periastron

**GR orbital, epicyclic and precessional freq**

General relativity:

\[ r_g \equiv \frac{GM}{c^2} \quad j \equiv \frac{Jc}{GM^2} \]

\[ v_\phi = \frac{\sqrt{GM} / r^3}{2\pi(1 + j(r_g / r)^{3/2})} \]

\[ v_r^2 = v_\phi^2(1 - 6(r_g / r) + 8j(r_g / r)^{3/2} - 3j^2 (r_g / r)^2) \]

\[ v_\theta^2 = v_\phi^2(1 - 4j(r_g / r)^{3/2} + 3j^2 (r_g / r)^2) \]
TWO POSSIBLE MISSION APPROACHES

**LOFT**
Large Observatory For x-ray Timing (ESA)

- Bright sources: Large Collimated Area

**eXTP**
enhanced X-ray Timing and Polarization mission (CAS)

- Weak/soft sources: Collimated + Focused Area
TWO POSSIBLE MISSION APPROACHES

LOFT
Large Observatory For x-ray Timing (ESA)

Bright sources:
Large Collimated Area

LOFT M4
RXTE
AstroSat
Athena
NICER
Astro-H
XMM

Energies (keV)

Effective Area (m²)

3.4m²

0.6m²
1m²

Weak/soft sources:
Collimated + Focused Area

eXTP
enhanced X-ray Timing and Polarization mission (CAS)

Effective Area (cm²)

3 x 10⁴
2 x 10⁴
3 x 10³
2 x 10³
1 x 10³
0
1
10
100

Energy (keV)
**THE LOFT SCIENTIFIC PAYLOAD**

**LAD - Large Area Detector**

| **Effective Area** | 3.4 m² @ 2 keV  
8.5 m² @ 8 keV  
0.8 m² @ 30 keV |
|-------------------|------------------|
| **Energy Range**  | 2-30 keV  
(30-80 keV ext.) |
| **Energy Resolution FWHM** | 200 eV @ 6 keV |
| **Collimated FoV** | 1 deg FWHM |
| **Absolute Time Accuracy** | 1 μs |

**WFM - Wide Field Monitor**

<table>
<thead>
<tr>
<th><strong>Field of View</strong></th>
<th>5.5 steradian</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Position Accuracy (10σ)</strong></td>
<td>1 arcmin</td>
</tr>
<tr>
<td><strong>Energy Range</strong></td>
<td>2-50 keV</td>
</tr>
<tr>
<td><strong>Energy Resolution</strong></td>
<td>300 eV @ 6 keV</td>
</tr>
<tr>
<td><strong>Collecting Area</strong></td>
<td>1460 cm²</td>
</tr>
</tbody>
</table>
| **Time Resolution** | 10 μs (trigger)  
~minutes (images) |
| **Sensitivity (5σ, Galactic Center)** | 330 mCrab (3s)  
2.1 mCrab (1day) |
| **Ground Transmission of GRB Coordinates** | < 30s |

**PROBING SPACETIME AND MATTER UNDER EXTREME CONDITIONS**
The eXTP Scientific Payload

11 X-ray optics, 6200 cm\(^2\) @6 keV, 4.5m FL, 1’
PSF, SDD (or CCD), 0.5-10 keV, <100 µs

2 X-ray optics, 1100 cm\(^2\) @6 keV, 4.5m FL,
15” PSF, GPD polarimeters, 2-10 keV

GPD polarimeter

LAD
Large Area Detector

LFA
Low-energy Focusing Array

WFM
Wide Field Monitor

3.4 m\(^2\) “LOFT” SDD detectors, 2-30 keV, <300 eV
@ 6 keV

3 units, 2-50 keV, 4 sr FoV, 80 cm\(^2\)/unit, 5’
angular resolution
Frequencies of motion in strong gravity

LOFT: 13x S/N

Inhomogeneities in inner disk

GR orbital, epicyclic and precessional frequencies

AB orbital cycle \([v_0]\)
AC vertical epicycle \([v_a]\)
BC nodal precession \([v_{0\phi}-v_0]\)

AB orbital cycle \([v_0]\)
AC radial epicycle \([v_r]\)
BC periastron precession \([v_{\phi-r}]\)
**RELATIVISTIC EPICYCLIC MOTION**

- Precisely measure orbital and epicyclic frequencies at each radius
- Compare curve to GR predictions
- Measure black hole mass and spin to 0.1% precision
Iron lines probe relativity predicted velocity and redshift map of the accretion disk

Line profile integrated over entire flow encodes:

- Strong field relativistic effect: Doppler shifts and boosting, gravitational redshift, strong field lensing

- Observed in Active Galactic Nuclei and X-ray binaries
Combining spectral and timing measurements: Orbiting spot: XMM observations of NGC3516

The excess emission map in the time–energy plane. The pixel size is 2 ks in time and 100 eV in energy. 4 cycles 25 ks orbital period at 9 Rg (XMM - Iwasawa+2004, Turner+2006)

\[ M_{\text{X-ray}} = 1 - 5 \times 10^7 \, M_{\text{sun}} \; ; \; M_{\text{opt}} = 1.68(0.33) \times 10^7 \, M_{\text{sun}} \]
Supermassive black hole

Orbital Doppler Tomography: AGN

LOFT 3 ks integrations

Orbital Doppler shift

Doppler shifting for orbits closely around a supermassive black hole

eXTP 1.5 ks 2x integrations

PROBING SPACETIME AND MATTER UNDER EXTREME CONDITIONS
**Stellar-mass black hole**

Orbital radial velocity curve at ISCO, closely around a **stellar mass** black hole.

Doppler tomography of disk velocity & redshift map.

Typical precision 1.5% in 100 ks

Uses **known** amplitude of quasi-periodic dynamic signals.
Reverberation: energy resolved light echoes

• Probe **disk velocity/redshift map** as radiation fronts propagate over the disk

• Relativistic effects as a function of **absolute radius** (e.g. km)
Precessing hot torus: variable geometry reverberation

- Frame dragging: central hot torus \textit{precesses}
- Hard radiation sweeps around over disk
- Reflection line profile varies periodically
- LOFT tracks the line profile, probing the disk velocity and redshift map
- Typical precision 0.3-3%

Polarization of processing inner torus

$R_o = 20R_g$, $a = 0.98$

- polarization degree and angle affected by strong field light bending
- precession changes geometry and thus modulates polarization

(Ingram+ 2015)
eXTP polarization measurements

- 32.768ks exposure
- $<p_0>=8\%$, $\sigma_{p_0}=1.4\%$, $<\psi_0>=-4$ degrees, $\sigma_{\psi_0}=4$ degrees
- Flux = 1 photon cm$^{-2}$s$^{-1}$ assuming absorbed power-law with $\Gamma=2$ and $N_h=1\times10^{22}$cm$^{-2}$
- 40 LAD modules, 2 GPD units
Variable Flux Reverberation

- Variable hot inner flow irradiates disk
- Probe disk velocity/redshift map as radiation fronts propagate over the disk
- Obtain strong field velocities and relativistic effects as a function of absolute radius

Reverberation detected in XMM data

LOFT improves S/N by
- factor ~6 in AGN
- factor >200 in X-ray binaries!

\[ R_{\text{in}} = 6 R_g \]
\[ R_{\text{in}} = 7 R_g \]
\[ R_{\text{in}} = 10 R_g \]
Disc reverberation components

10 FA + 40LAD

\[
R_{\text{in}} = 6 \ R_g \\
R_{\text{in}} = 7 \ R_g \\
R_{\text{in}} = 10 \ R_g
\]

In addition to the iron line and reflection continuum, the absorbed flux is reradiated by the disc as thermal blackbody radiation.

eXTP can study all three components simultaneously!
LOFT’s strong gravity arena: accreting black holes

X-ray binary system

Active galactic nucleus

LOFT and eXTP cover wide mass range in uniform setting

Stellar mass black hole (or neutron star)

Strongly curved spacetime. \((10^{16} \text{ times Solar})\)

Supermassive black hole

Weakly curved spacetime \((\sim \text{Solar})\)

Complementary to gravitational wave experiments: LOFT probes stationary spacetimes
Test alternative theories of gravity through X-ray diagnostics like Fe-lines and QPOs.

factor $10^{12}$ in curvature

factor $10^5$ in field strength

after Psaltis 2008
CONCLUSIONS

• X-ray timing, spectral and spectral/timing diagnostics of accreting black holes will allow us to:
  - verify for the 1st time key predictions of GR in the strong field regime
  - test or constrain some alternative theories of gravity

• Very high throughput combined with good spectral resolution is required:
  two different missions are being studied, LOFT and eXTP

THANK YOU