Toward a Space-based Gravitational Wave Observatory

Robin Stebbins, GSFC
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Outline

• History
• Science
• Concepts
• Current activities
  • LISA Pathfinder
  • ESA’s L3
  • Technology
  • Near term activities
A BRIEF HISTORY OF GRAVITATIONAL WAVES IN SPACE
A Brief History of LISA, NASA & ESA

• 1974 - A dinner conversation and NASA report
• 1985 – LAGOS Concept (Faller, Bender, Hall, Hils and Vincent)
• 1993 – LISAG - ESA M3 study: six S/C LISA & Sagittarius
• 1997 - JPL Team-X Study: 3 S/C LISA
• 2000 – Decadal recommendation for new start
• 2001-2015 - LISA Pathfinder and ST-7 DRS
• 2001 – NASA/ESA project began
• 2004 – Phase A started
• 2007 – NRC BEPAC Review
• 2010 – Decadal recommendation for new start
• 2011 – NASA/ESA project ended
• 2013 – ESA selects GW mission for L3
The history of major reviews

The LISA concept has always gotten high rankings in NRC reviews:

• AANM (2000) decadal: highest priority medium new start
• Quarks to Cosmos: proceed to develop
• Beyond Einstein Program: highest priority science
• NWNH (2010) decadal: second priority large mission after WFIRST
GRAVITATIONAL WAVE SCIENCE
Gravitational Wave Spectrum

Credit: Teviet Creighton
Origin and growth of massive black holes

• Observe: MBHs from $10^3$ to $10^7 \, M_\odot$, $z<20$ radiate in LISA band as some point; 10’s of events per year

• Measure: masses, spin vectors, luminosity distance, sky position, etc.

• Learn about:
  • MBH seed population
  • Growth mechanisms vs redshift
  • Merger history before earliest quasars
Stellar populations and dynamics in galactic nuclei

- Observe: stellar mass compact objects spiraling into MBHs (EMRIs), $z \lesssim 1$; 10’s-100’s of events per year
- Measure: masses, spin vectors, luminosity distance, sky position, etc.
- Learn about:
  - Stellar populations in galactic nuclei
  - Intermediate mass BHs
  - Detailed geodesy of MBH spacetime
Compact stellar-mass binaries and structure of the galaxy

- Observe: millions of close compact binaries in the galaxy, tens of thousands individually resolvable, some electromagnetically observed.
- Measure: chirp mass or individual masses if evolving, orbital parameters, period evolution if interacting
- Learn about:
  - Demographics
  - Shape of the galaxy
  - Close binary evolution
  - Type 1a progenitors
Fundamental Physics and Cosmology

- Observe: waveform evolution, merger dynamics, higher harmonics in ring-down, spacetime mapping
- Measure: precise waveform phase and amplitude, luminosity distances over a wide range of redshifts, waveforms with electromagnetic counterparts
- Learn about:
  - Test GR in dynamical, strong-field gravity, constrain alternative theories
  - Fundamental properties of GWs: speed of propagation, polarization states
  - Fundamental properties of black holes: no-hair, Kerr
  - Hubble expansion out to large redshifts
  - Cosmic expansion history, geometry and dark energy
  - Exotic and unforeseen sources
Recent Advances in GW Astrophysics

- Improvements in MBHB parameter estimation
  - Added merger and ring-down phases to waveforms
  - Added higher harmonics to waveforms
  - Improved understanding of sky localization, especially from merger phase
  - Orbital eccentricity explored
  - Improved understanding of the interaction between SMBHs and their host galaxies, including effects of eccentricity and spin alignments
  - Kicks explored
  - Improved cosmological modeling of structure formation
  - Better understanding of final parsec problem and its resolution

- Emerging methods for quantifying GR tests
- Improved galaxy models
- Science performance calculations
  - ~50 mission concept variants analyzed
2010s – The GW Decade

Advanced LIGO/Virgo/KAGRA begin operations
- O1 observing run began September 18th for 3 months
- Reach 70 Mpc for NS-NS mergers, 3 times previous LIGO distance (27 times volume)
- Progressive sensitivity improvement in next few years
- First GW observations expected by ~2019

Pulsar Timing Arrays (PTAs)
- PTA efforts have published upper-limits on stochastic GW backgrounds from SMBH binary mergers (NANOGrav, EPTA, PPTA)
- A key astrophysical uncertainty is in the strength of SMBH binary interactions with their environments
- Recent (2015) results from Parkes (PPTA) are in conflict with models that assume modest rates of evolution passing through the nHz band.
- Models less sensitive to environmental effects at higher frequencies

LISA Pathfinder launch and operation
MISSION CONCEPTS
LISA Concept

- Measure changes in ‘time-of-flight’ between test masses
  - Continuous laser ranging between free-falling test masses
  - Interferometric readout (μcycles/√Hz over gigameters with 1μ light)
  - Performance characterized by noise in measurement of displacement

- Reduce disturbances on those test masses
  - Benign environment
  - Enclosed test masses
  - Control disturbances from spacecraft
  - Limit relative motion of spacecraft with “drag-free” control
  - Performance characterized by residual acceleration noise
LISA Concept
Mission Concept Study

In 2012 NASA studied the impact of design trade-offs on science, cost and risk, looking for a mission concept ≤$1B.

The findings can be summarized as follows:

- No concepts were found near or below $1B.
- No technology was found that dramatically reduces cost.
- The LISA architecture can be scaled down somewhat, and still do compelling science.
- Science performance decreases far more rapidly than cost. At some point, risk increases to an unacceptable level for missions of this scale.
# Mission Concept Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NGO</th>
<th>SGO Mid</th>
<th>LISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement arm length</td>
<td>1 x 10^6 km</td>
<td>1 x 10^6 km</td>
<td>5 x 10^6 km</td>
</tr>
<tr>
<td>Number &amp; type of spacecraft</td>
<td>1 corner (2 optical assemblies, 2 end (single optical assembly)</td>
<td>3 corner (2 optical assemblies)</td>
<td>3 corner (2 optical assemblies)</td>
</tr>
<tr>
<td>Number of measurement arms, one-way links</td>
<td>2 arms, 4 links</td>
<td>3 arms, 6 links</td>
<td>3 arms, 6 links</td>
</tr>
<tr>
<td>Constellation</td>
<td>Vee</td>
<td>Triangle</td>
<td>Triangle</td>
</tr>
<tr>
<td>Gravitational-wave polarization measurement</td>
<td>Single instantaneous polarization, second polarization by orbital evolution</td>
<td>Two simultaneous polarizations continuously</td>
<td>Two simultaneous polarizations continuously</td>
</tr>
<tr>
<td>Orbit</td>
<td>Heliocentric, earth-trailing, drifting-away 9° - 21°</td>
<td>Heliocentric, earth-trailing, drifting-away 9° - 21°</td>
<td>22° heliocentric, earth-trailing</td>
</tr>
<tr>
<td>Trajectory</td>
<td>Launch to Geosynchronous Transfer Orbit, transfer to escape, 14 months</td>
<td>Direct injection to escape, 18 months</td>
<td>Direct injection to escape, 14 months</td>
</tr>
<tr>
<td>Duration of science observations</td>
<td>2 years</td>
<td>2 years</td>
<td>5 years</td>
</tr>
<tr>
<td>Launch vehicle</td>
<td>Two Soyuz-Fregat</td>
<td>Single Medium EELV (e.g., Falcon 9 Block 3)</td>
<td>Single Medium EELV (e.g., Atlas V 551)</td>
</tr>
<tr>
<td>Optical bench</td>
<td>Low-CTE material, hydroxy-catalysis construction</td>
<td>Low-CTE material, hydroxy-catalysis construction</td>
<td>Low-CTE material, hydroxy-catalysis construction</td>
</tr>
<tr>
<td>Laser</td>
<td>2 W, 1064 nm, frequency and power stabilized</td>
<td>1 W, 1064 nm, frequency and power stabilized</td>
<td>2 W, 1064 nm, frequency and power stabilized</td>
</tr>
<tr>
<td>Telescope</td>
<td>20 cm diameter, off-axis</td>
<td>25 cm diameter, on-axis</td>
<td>40 cm diameter, on-axis</td>
</tr>
<tr>
<td>Gravitational Reference Sensor</td>
<td>46 mm cube Au:Pt, electrostatically controlled, optical readout</td>
<td>46 mm cube Au:Pt, electrostatically controlled, optical readout</td>
<td>46 mm cube Au:Pt, electrostatically controlled, optical readout</td>
</tr>
</tbody>
</table>
## Science Comparison

<table>
<thead>
<tr>
<th>Source</th>
<th>NGO</th>
<th>SGO Mid</th>
<th>LISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBH Totals</td>
<td>40-47</td>
<td>41-52</td>
<td>108-220</td>
</tr>
<tr>
<td>Detected $z &gt; 10$</td>
<td>1-3</td>
<td>1-4</td>
<td>3-57</td>
</tr>
<tr>
<td>Both mass errors $&lt; 1%$</td>
<td>13-30</td>
<td>18-42</td>
<td>67-171</td>
</tr>
<tr>
<td>One spin error $&lt; 1%$</td>
<td>3-10</td>
<td>11-27</td>
<td>49-130</td>
</tr>
<tr>
<td>Both spin errors $&lt; 1%$</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1-17</td>
</tr>
<tr>
<td>Distance error $&lt; 3%$</td>
<td>3-5</td>
<td>12-22</td>
<td>81-108</td>
</tr>
<tr>
<td>Sky location $&lt; 1 \text{deg}^2$</td>
<td>1-3</td>
<td>14-21</td>
<td>71-112</td>
</tr>
<tr>
<td>Sky location $&lt; 0.1 \text{deg}^2$</td>
<td>&lt;1</td>
<td>4-8</td>
<td>22-51</td>
</tr>
<tr>
<td>EMRIIs</td>
<td>12</td>
<td>35</td>
<td>800</td>
</tr>
<tr>
<td>Resolved CWDBs</td>
<td>3,889</td>
<td>7,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Interacting</td>
<td>50</td>
<td>100</td>
<td>1,300</td>
</tr>
<tr>
<td>Detached</td>
<td>5,000</td>
<td>8,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Sky location $&lt; 1 \text{deg}^2$</td>
<td>1,053</td>
<td>2,000</td>
<td>13,000</td>
</tr>
<tr>
<td>Sky location $&lt; 1 \text{deg}^2$, distance error $&lt; 10%$</td>
<td>533</td>
<td>800</td>
<td>8,000</td>
</tr>
<tr>
<td>Stochastic Background</td>
<td>0</td>
<td>0.2</td>
<td>1</td>
</tr>
</tbody>
</table>

Special acknowledgement to Ryan Lang (Univ. of Florida) and Neil Cornish (Montana State Univ.)
LISA PATHFINDER
LISA Pathfinder

- Mission to demonstrate technology for a LISA-like gravitational wave observatory.
- European payload has Gravitational Reference Sensors, interferometer and “drag-free” control system.
- NASA participation in European payload operations and data analysis.
- NASA payload, called ST7 Disturbance Reduction System, has micronewton thrusters and “drag-free” control system.
- Launch in December 2015.
LPF – The Basic Idea

• Drag-free control system
  • One test mass as a sensor
  • Microthruster as a forcer.
  • Controller
• Second test mass as a “witness.”
• Measure the relative motions of the two test masses with picometer interferometer
LPF Objectives

• Drag-free flight demonstration
  • Residual acceleration on the test mass <3×10^{-14} \text{ m/sec}^2/\sqrt{\text{Hz}} \text{ at 1 mHz}
  • Multi-degree-of-freedom control system

• Microthruster demonstration
  • Thrust noise
  • Controllability

• Error budget validation
  • Programmable environment disturbances (magnetic, thermal, charging)
  • Measure the transfer function
  • Extrapolate to LISA
LPF – Status

• Design, fabrication, assembly and test of the flight system completed September 1\textsuperscript{st}
• Final ground testing \textit{met or exceeded} all requirements.
• October 8: Flown to Kourou, start of the launch campaign
• December 1, 11:15 pm EST: scheduled launch on Vega 6 (38 days, 8 hours, 21 minutes @ 3:54 pm EDT)
• L+74 d: LTP operations start
• L+186 d: ST7 operations start
• L+288 d: Nominal mission ends.
• Extended mission under consideration.
LPF in Kourou Processing Facility
The prototype telescope is shown in Fig. 3. The drawing on the left illustrates the central, or “gut” ray’s path through the telescope indicated by the solid brown line. The secondary is in the light blue mount to the left of the primary. The photo on the right is the telescope as aligned in the vendor’s cleanroom.

Both the telescope and the scattered-light test-bed are installed in the Laser Communication Relay Demonstration (LCRD) cleanroom, where we have arranged to share the space through the end of the calendar year. This arrangement allows us access to the clean room environment, which helps postpone the degradation we expect from particulate contamination. It also enables access to a key piece of test equipment (an interferometer). In return, LCRD has access to a key piece of our test equipment, a point-source microscope.

The immediate next step is to re-assemble and re-align the telescope. We expect alignment to take approximately three weeks, and then we will begin stray-light testing. The goal is to complete these measurements, and measurements with the scattered-light test-bed, by September 2015 (see Fig. 2). The desired result is a validation of the scattered-light model we have developed, not necessarily to achieve a specific level of performance. Understanding the model will allow us to better design a follow-on telescope to meet the required level of performance. In some cases this may result in a reduction in risk and cost as we understand which aspects of the design, particularly the mirror design, are essential and which are not.

Scattered-light suppression work was augmented with funding received by Ron Shiri through the GSFC Internal Research and Development (IRAD) program for development of partially transparent petaloid masks. This funding enabled Ron to engage with the University of Delaware for fabrication of partially transparent masks. Experimental efforts continue with Shannon Sankar making transmission measurements of the petaloid masks designed by Ron. The goal is to understand the challenges and limitations of the different steps that must be followed to progress from a theoretical design to a working mask. A number of fabrication methods have been tested, and we are in the process of a quantitative comparison between theory and experiment for a circular mask for which we can calculate the expected response analytically. A publication is in preparation.

Successful implementation of these masks may allow us to adopt an on-axis telescope design, which may be less expensive to build and better suited to the application’s environmental requirements compared to an off-axis design.
Technology Development

- Telescope Subsystem – Jeff Livas (GSFC)
  - Demonstrate pathlength stability, stray light and manufacturability
- Phase Measurement System – Bill Klipstein (JPL)
  - Key measurement functions demonstrated
  - Incorporate full flight functionality
- Laser Subsystem – Jordan Camp (GSFC)
  - 1064 nm ECL master oscillator
  - Phase noise of fiber power amplifier
  - Demonstrate end-to-end performance in integrated system
  - Lifetime
- Micronewton Thrusters – John Ziemer (JPL)
  - Propellant storage and distribution for long duration
  - Improve system robustness
  - Improve manufacturing yield
  - Lifetime
Technology Development

• Arm-locking Demonstration – Kirk McKenzie (JPL)
  • Studying a demonstration of laser frequency stabilization with GRACE Follow-On

• Torsion Pendulum – John Conklin (UF)
  • Develop U.S. capability with GRS and torsion pendulum test bed

• Multi-axis Heterodyne Interferometry – Ira Thorpe (GSFC)
  • Investigate test mass/optical bench interface

• UV LEDs – John Conklin (UF)
  • Flight qualify UV LEDs to replace mercury lamps in discharging system

• Optical Bench – Guido Mueller (UF)
  • Investigate alternate designs and fabrication processes to ease manufacturability

LISA researchers at JPL are leading the Laser Ranging Interferometer instrument on the GRACE Follow-On mission.
ESA’S COSMIC VISION PROGRAMME 2015-2025
Cosmic Visions 2015-2025

• Next “planning horizon” for ESA science
• NASA withdrew from initial L1 competition in 2011.
• Next Gravitational Observatory (NGO) concept proposed to second L1 competition in 2012.
  • Descoped LISA-like mission to meet ESA cost cap without US participation
  • *Two arms, 1 million Km baselines, 2 year science operations, 2 launches, mother-daughter configuration.*
  • JUICE selected
• “Gravitational Universe” proposed for L2/L3 Competition in 2013
  • NGO the “notional” mission concept.
  • Senior Selection Committee selected Athena for L2 and the Gravitational Universe as the “science theme” for L3, because LPF had not flown.
ESA’s L3 Mission

• Only ‘science theme’ selected, not a mission concept
• Planned launch date is 2034.
• Cost cap is 1B€ to ESA.
• Member states typically contribute an additional 30-35%.
• International partners limited to 20% of total European contribution (about $300M).
• The Astrophysics Strategic Plan calls for NASA to participate as a partner in L3.
• NASA is currently negotiating for a $100-150M contribution. Significantly more would be spent within the US.
• ESA included three U.S. members and one NASA observer on the Gravitational Observatory Advisory Team (GOAT)
NEAR TERM
NASA activities in the near term

- Operations and data analysis on Pathfinder and ST7
- GW Science Interest Group/Physics of the Cosmos Program Analysis Group (POCs: John Conklin and Neil Cornish)
- Continued participation in ESA’s GOAT
- Participation in early ESA lead-in activities: mission concept proposal/selection, Phase A start in 2017, ...
- Technology development to meet the L3 schedule (ISO TRL6 by Q4 2019)
- NRC Midterm review: in progress, first meeting in October, workshop in December, final meeting in January
- Pre-decadal study in 2017-2018
- Preparations for next decadal (Astro2020)
Summary

• A space-based GW observatory will produce spectacular science.

• The LISA mission concept
  • Long history
  • Very well-studied, including de-scopes

• NASA’s Astrophysics Strategic Plan calls for a minority role in ESA’s L3 mission opportunity.

• To that end, NASA is
  • Participating in LPF and ST7
  • Developing appropriate technology for a LISA-like mission
  • Preparing to seek an endorsement for L3 participation from the 2020 decadal review