The Gravitational Universe and LISA

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Introduction

LISA - the Laser Interferometer Space Antenna - is a European Space Agency mission to observe low frequency gravitational waves from space.

LISA has been around for over 20 years, with a science case which has remained stable over the years. However, there was always doubts that:

1. Gravitational waves do not exist!
2. Even if they did, we are not capable of building an instrument sensitive enough, let alone in space, which can measure the miniscule effect of a passing GW

Then came the second half of 2015....

- LIGO makes first direct detection of gravitational waves, GW150914 → 14 September 2015
- LISA Pathfinder launched → 3 December 2015
  - LISA Pathfinder performance surpasses all expectations

Both momentous events opened the door to the **Gravitational Universe**
Gravitational waves...what are they?

- Newton’s theory of gravity:
  - “instantaneous action at a distance”

- Einstein’s Special Theory of Relativity:
  - “information cannot be carried faster than the speed of light”
  - There must be something to carry the gravitational information

- Gravitational waves:
  - Ripples in the curvature of spacetime
  - Produced by the motion of mass and energy
Gravitational waves...what are they?

- Newton’s theory of gravity:
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- Einstein’s Special Theory of Relativity:
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- Gravitational waves:
  - Ripples in the curvature of spacetime
  - Produced by the motion of mass and energy
  - Travel through the Universe (almost) unimpeded
  - Allows us to observe the very distant universe
  - Difficult to detect!

Gravitational Waves carry entirely new information about the Universe
What happens when a GW passes Earth?

Earth Diameter: ~12,800km

Passage of gravitational wave:
Earth's diameter changes by ~1/10,000 the diameter of an atom!
Ground based GW detectors

- **LIGO: Hanford, WA**
- **LIGO: Livingston, LA**
- **VIRGO: Cascina, Italy**
- **GEO600: Ruthe, Germany**
- **KAGRA: Kamioka Japan**
The first direct detection...GW150914

[Abbott et al, PRL 2016]
What did LIGO observe?
What did LIGO observe?
GW150914 was not alone...
Multi-messenger astronomy - GW170817
Multi-messenger astronomy - GW170817

Aug. 18

1 arcminute
Multi-messenger astronomy - GW170817

**Fermi**
Reported 16 seconds after detection

**LIGO-Virgo**
Reported 27 minutes after detection

**INTEGRAL**
Reported 66 minutes after detection

**Gamma rays, 50 to 300 keV**
- **GRB 170817A**

**Gravitational-wave strain**
- **GW170817**
  - 1.7 secs

**Gamma rays, 100 keV and higher**
- **GRB 170817A**

Graphs showing data from Fermi, LIGO-Virgo, and INTEGRAL.
How important are these discoveries?
How important are these discoveries?
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How important are these discoveries?

President Obama @POTUS44

Einstein was right! Congrats to @NSF and @LIGO for the discovery of gravitational waves - a huge breakthrough for science. Let's use this moment to understand the universe.
12:43 AM - 12 Feb 2016

9,136 replies 21,246 likes
GW Spectrum

The Gravitational Wave Spectrum

Sources

Wave Frequency

Wave Period

10^{-18} 10^{-14} 10^{-10} 10^{-6}

years

10^{-4} 10^{-2} 1

seconds

10^2

milliseonds

CMB Polarization

Radio Pulsar Timing Arrays

Space-based interferometers

Terrestrial interferometers

(v_{gw} \downarrow (\lambda_{gw} \uparrow)) \Rightarrow L_{armlength} \uparrow
What will we learn with LISA?

The science objectives of LISA include:

- **Study the formation and evolution of compact binary stars in the Milky Way**
  - Compact binaries emit continuous and nearly monochromatic GW signals in the source frame
  - Several galactic binaries have already been observed electromagnetically, and will be used as verification sources for the LISA instrument performance
  - Galactic binaries will form a confusion noise *foreground* limiting LISA performance at frequencies around 1mHz

- **Objectives:**
  - Period precision: $\delta P/P < 10^{-6}$
  - Mass, distance and sky location for fraction of GBs, with $d < 15\text{kpc}$
  - For ~10,000 systems, locate to $<1\text{deg}^2$ to allow EM follow-up

<table>
<thead>
<tr>
<th>SciRD</th>
<th>Individually Resolved</th>
<th>$\delta P/P &lt; 10^{-6}$</th>
<th>Sky location for EM counterpart</th>
<th>Sky location for EM c-part + $\delta f$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24,500</td>
<td>21,000</td>
<td>10,000</td>
<td>5,200</td>
</tr>
</tbody>
</table>
What will we learn with LISA?

The science objectives of LISA include:

- Study the formation and evolution of compact binary stars in the Milky Way
- **Trace the origin, growth and merger history of massive black holes across cosmic ages**
  - The origin of the massive/supermassive black holes powering AGN and sitting at the centres of today’s galaxies is unknown
  - LISA will be able to observe seed black holes back to Cosmic Dawn

**Objectives:**
- Observe the first compact objects in the Universe (seed black holes) out to $z \sim 15$
- Masses, and distance to Supermassive Black Hole mergers ($10^6 M_\odot$) mergers at $z < 9$
  - Masses to 1%, Distance to 10%, Spin to 1-10% precision
- Sky location to $<10\deg^2$ for SMBH mergers at $z \sim 2$ for EM follow-up
Future EM obs. e.g. LSST, JWST, EELT

Future ground based detectors e.g. Einstein Telescope

Current ground based GW detectors

SKA, Pulsar Timing

Black Hole Astronomy in the 2030s
What will we learn with LISA?

The science objectives of LISA include:

- Study the formation and evolution of compact binary stars in the Milky Way
- Trace the origin, growth and merger history of massive black holes across cosmic ages
- **Prove the dynamics of dense nuclear clusters using EMRIs**
  - EMRIs describe the inspiral and final plunge of Stellar-Origin BH in the range of $10^{-60}M_\odot$ into MBH of $10^5-10^6M_\odot$
  - EMRIs are essentially the perfect laboratory to test GR in the strong field regime
    - The SOBH spends $\sim 10^3-10^5$ orbits in close proximity to the MBH, displaying extreme forms of perisaostron and orbit plane precession
- **Objectives**:
  - Observation of EMRIs out to $z=4$ with SNR >20
  - $\delta M/M < 10^{-4}$, $\delta m/m < 10^{-3}$
What will we learn with LISA?

The science objectives of LISA include:

- Study the formation and evolution of compact binary stars in the Milky Way
- Trace the origin, growth and merger history of massive black holes across cosmic ages
- Probe the dynamics of dense nuclear clusters using EMRIs

- **Understand the astrophysics of stellar origin black holes**
  - As the SOBH inspiral towards final merger, the gravitational wave signal will sweep through the LISA band
  - LISA will observe the inspiral or months to years prior to merger
    - The signal will leave the LISA band weeks before final merger

- **Objectives:**
  - Sky location of <1deg² of GW150914-like events (SNR>7 after 3 years integration)
  - Orbit eccentricity to better than 1 part in 10³
What will we learn with LISA?

The science objectives of LISA include:

- Study the formation and evolution of compact binary stars in the Milky Way
- Trace the origin, growth and merger history of massive black holes across cosmic ages
- Probe the dynamics of dense nuclear clusters using EMRIs
- Understand the astrophysics of stellar origin black holes
- **Explore the fundamental nature of gravity and black holes**
  - SMBH binaries and EMRIs enable tests of GR in the strong field regime
  - Precision tests require *Golden binaries* with SNR >100 (SMBHB) or >50 (EMRIs)
- **Objectives:**
  - Test “no-hair” theorem of GR
  - Explore multipolar structure of MBH
The science objectives of LISA include:

- Study the formation and evolution of compact binary stars in the Milky Way
- Trace the origin, growth and merger history of massive black holes across cosmic ages
- Probe the dynamics of dense nuclear clusters using EMRI
- Understand the astrophysics of stellar origin black holes
- Explore the fundamental nature of gravity and black holes
- **Probe the rate of expansion of the Universe**
  - Source distance is proportional to GW amplitude, chirp rate, and GW polarisation
  - GW sirens: EMRI (z<1.5), SMBHB (z<6)

- **Objectives:**
  - $H_0$ with accuracy of <1% with only GW observations
  - Improved if we also observe the source e.g. with Athena
What will we learn with LISA?

The science objectives of LISA include:

- Study the formation and evolution of compact binary stars in the Milky Way
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- Explore the fundamental nature of gravity and black holes
- Probe the rate of expansion of the Universe
- **Understand stochastic GW backgrounds and their implications for the early Universe**
  - LISA goal is to directly detect a stochastic GW background of cosmological origin
  - The shape of the signal gives an indication of its origin, while an upper limit constrains models of the early universe
What will we learn with LISA?

The science objectives of LISA include:
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- Probe the rate of expansion of the Universe
- Understand stochastic GW backgrounds and their implications for the early Universe
- **Search for GW bursts and unforeseen sources**
  - First LIGO observations came from unexpected sources…
  - …what will LISA see?
LISA discovery space

The diagram illustrates the strain PSD (strain per square root of frequency) as a function of frequency. The axes are labeled as Strain PSD (Hz^-1/2) on the y-axis and Frequency (Hz) on the x-axis. Various lines represent different categories, such as Galactic Binaries, seed black holes at high redshifts, and others. The diagram also includes labels for sensitivity envelopes, goal, and permitted relaxation conditions.
L3 - LISA

The Gravitational Universe

Call for mission to meet L3 Science Theme (October 2016)

LISA Proposal (January 2017)

LISA Selected as L3 mission (June 2017)
LISA Mission Concept

- Cluster of 3 spacecraft in a heliocentric orbit
  - 3 coupled “Michelson-like” interferometers in space
  - Allows measurement of amplitude and polarisation of GW
  - Spacecraft shield the test masses from external forces (solar wind, radiation pressure)
LISA Mission Concept

- Cluster of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by $\sim 20^\circ$ (50 million km)
  - Reducing the influence of the Earth-Moon system on the orbits
  - Keeping the communication requirements (relatively) standard
LISA Mission Concept

- Cluster of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by ~20° (50 million km)
- Equilateral triangle with 2.5 million km arm length
  - Results in measurable pathlength variations due to passage of GW
  - Orbit is stable enough to allow for mission duration of 10 years without active orbit maintenance
Cluster of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by ~20° (50 million km)
- Equilateral triangle with 2.5 million km arm length
- Inclined with respect to ecliptic plane by 60°
  - Required by orbital mechanics
The LISA Orbit

- Constellation counter-rotates during the course of the year
- No additional orbit control necessary
- Constellation forms an “almost rigid” triangle
LISA

- Laser beams transmitted through 30cm off-axis telescopes
- Diffraction widens beam to several kilometres
  - ~1.5W transmitted, ~500pW received
  - LISA cannot form Fabry-Perot cavities in the arms as in LIGO
- 12 separate interferometric measurements made
  - 6 arm lengths
  - 6 test mass -> spacecraft
- Time-Delay Interferometry (TDI) used to synthesise equal arm interferometer (ala LIGO)
- 3 semi-independent Michelson interferometers
  - Constellation also provides Sagnac interferometer
- Orbital motion provides direction information
LISA Sensitivity Curve
LISA Pathfinder was designed to test the critical technologies for LISA, namely:
- Free-falling test mass
- Pico-metre resolution displacement sensing
- Drag free satellite control
- Micro-Newton proportional thruster systems
LPF On-orbit results: Displacement noise

LPF local interferometer is approx. 300 times better than requirements (and ~30 times better than equivalent LISA requirement)
The differential acceleration between the test masses (known as “delta-g”) is the primary performance requirement of the mission…

…and was met during commissioning!
LPF on-orbit results: Differential Acceleration

![Graph showing differential acceleration vs frequency](image-url)
Platform stability

Size of human Rhinovirus (~30nm)
LPF to LISA

Image courtesy of NASA - GSFC
LPF to LISA
LPF to LISA
## Current status and schedule

<table>
<thead>
<tr>
<th>Event</th>
<th>From</th>
<th>To</th>
<th>Status</th>
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<tbody>
<tr>
<td>Mission Phase 0 (CDF)</td>
<td>2017-Mar</td>
<td>2017-May</td>
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<tr>
<td>Phase 0 for instrument contributions</td>
<td>2017-JUL</td>
<td>2017-NOV</td>
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<tr>
<td>Mission Definition Review (MDR)</td>
<td>2017-NOV-27</td>
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<td>Phase A (mission &amp; payload)</td>
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<td>2020-Jan</td>
<td>Ongoing</td>
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<td>Mission Formulation Review (MFR)</td>
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<td>2019-DEC</td>
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<td>Implementation (Phase B2/C/D)</td>
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<td>Transfer &amp; Commissioning</td>
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<td>Operations</td>
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<td>Extension (TBD)</td>
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<td>10 years total of science</td>
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Conclusions

- LISA Pathfinder on-orbit performance has far exceeded the pre-launch requirements
  - (Local) interferometer displacement noise floor: ~35fm/√Hz at high frequencies
  - Differential acceleration noise: < 2fms^2/√Hz at ~mHz frequencies
    …LISA performance met across full LISA measurement goal!
- LPF performance, along with LIGO observations, have pushed forward the LISA development programme
- Gravitational wave astronomy is a reality
  - LISA opens the window to the low frequency GW spectrum
- For more information on LISA, please visit:
  - sci.esa.int/LISA
  - www.lisamission.org

LISA Consortium:
- signup.lisamission.org