LISA: Using Gravitational Waves To Probe Black Hole Physics and Astrophysics

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LISA - The Overview

**Mission Description**
- 3 spacecraft in Earth-trailing solar orbit separated by $5 \times 10^6$ km.
- Gravitational waves are detected by measuring changes in distance between fiducial masses in each spacecraft using laser interferometry
- Partnership between NASA and ESA
- Launch date ~2012+

**Observational Targets**
- Mergers of massive black holes
- Inspiral of stellar-mass compact objects into massive black holes
- Gravitational radiation from thousands of compact binary systems in our galaxy
- Possible gravitational radiation from the early universe
This Talk:

- Gravitational waves and gravitational wave sources
- LISA mission concept
- LISA BH science capabilities
  - Extreme Mass Ratio Inspirals
  - Massive BH Mergers
Gravitational Waves

- **Two polarizations of GWs**
  \[ T_{GW} \]
  \[ \begin{array}{c|cccc}
    & 0 & \pi/2 & \pi & 3\pi/2 \\
    \text{pol.} & \begin{array}{c}
      \text{L } \\
      \text{L + } \delta \text{l }
    \end{array}
    & \begin{array}{c}
      \text{L } \\
      \text{L - } \delta \text{l }
    \end{array}
    & \begin{array}{c}
      \text{L } \\
      \text{L }
    \end{array}
    & \begin{array}{c}
      \text{L } \\
      \text{L - } \delta \text{l }
    \end{array}
  \end{array} \]

- **Laser interferometer**

\[ h = \frac{\Delta L}{L} \]
\[ P_{OUT} = P_{IN} \cos^2(2k\Delta L) \]

References:
- Pirani, '56
- Gertsenshtein and Pustovoit, '62
- Weiss, '72
- Forward, '72

(N. Mavalvala)
How big might $h$ be for a typical LISA source?

- Use Newtonian/quadrupole approximation to Einstein Field Equations:

$$h = \frac{\Delta L}{L} \sim \left( \frac{G}{c^4} \right) \frac{\ddot{Q}}{r}$$

[ $\ddot{Q}$ is the second time derivative of the source mass quadrupole]

$$h \sim \frac{1}{c^2} \frac{4G(E_{kin}^{non-sphere}/c^2)}{r} \sim \frac{4GM_{equiv}}{rc^2}$$

- That is, $h$ is about 4 times the dimensionless gravitational potential at Earth produced by the mass-equivalent of the source’s non-spherical, internal kinetic energy

$\Rightarrow h \sim 10^{-18}$ for $10^6 M_\odot$ BH merger at $10$ Gpc

(Compare to typical $10^{-21}$ to $10^{-23}$ sensitivity of LISA)
Ground-based Gravitational Wave Detectors

- LIGO, VIRGO, GEO, TAMA … ca. 2003
  - 4000m, 3000m, 2000m, 600m, 300m interferometers built to detect gravitational waves from compact objects
Complementarity of Space- & Ground-Based Detectors

Difference of $10^4$ in wavelength:
Like difference between X-rays and IR!
LISA Mission Concept
Orbits

- Three spacecraft in triangular formation; separated by 5 million km
- Spacecraft have constant solar illumination
- Formation trails Earth by 20°; approximately constant arm-lengths

1 AU = 1.5x10^8 km
Determining Source Directions

- Two methods: AM & FM
- **FM**: Frequency modulation due to LISA orbital doppler shifts
  - Same as using pulsar timing over 1 year to get positions
  - Typical resolution: 1 deg: \((10^{-3} \text{ Hz and SNR}=10^3)\) or \((10^{-2} \text{ Hz and SNR}=10)\)
  - FM gives best resolution for \(f > 1 \text{ mHz}\)
- **AM**: Amplitude modulation due to change in orientation of array with respect to source over the LISA orbit
  - AM gives best resolution for \(f < 1 \text{ mHz}\)
  - Typical resolution: 1 deg for SNR=10\(^3\); 10 deg for SNR=10
- **Summary**: LISA will have degree level angular resolution for many sources (sub-degree resolution for strong, high-frequency sources)
  - See e.g. Cutler (98), Cutler and Vecchio (98), Moore and Hellings (00), also Hughes (02)
Determining Source Distances

- Binary systems with orbital evolution \((\text{df}/\text{dt})\)
  - “Chirping” sources
  - Determine the luminosity distance to the system by comparing amplitude, \(h\), and period derivative, \(\text{df}/\text{dt}\), of the gravitational wave emission
  - Quadrupole approximation:

\[
h \propto \frac{M_{\text{Chirp}}^{5/3}}{D_L} f^{2/3} \\
\dot{f} \propto M_{\text{Chirp}}^{5/3} f^{11/3}
\]

- Implies luminosity distance \((D_L)\) can be estimated directly from the detected waveform
- See e.g. work by Hughes, Vecchio for quantitative estimates
LISA Sensitivity

2-arm “Michelson” sensitivity \( h \times \sqrt{T_{\text{obs}}} \)

\[
\text{Spectral amplitude, } S_f(f) \left[ \text{Hz}^{-1/2} \right]
\]

- Acceleration Noise (Disturbance Level)
- Short-\( \lambda \) Limit
- Shot Noise (Measurement Sensitivity)

0.1 mHz \( \rightarrow \) 1 Hz

frequency

(Includes gravitational wave transfer function averaged over sky position and polarization). Source sensitivities plotted as \( h \times \text{Sqrt(Tobs)} \).
LISA Interferometry

- **Components**
  - 1 W lasers
  - 30 cm telescopes
  - Drag-free proof masses
  - Optical fiber coupling between assemblies on same S/C

- **Measurements**
  - 6 laser Doppler signals between S/C
  - 6 reference beams between S/C assemblies
Spacecraft

- **Two optical assemblies**
  - Proof mass and sensors
  - 30 cm telescope
  - Interferometry: 20 pm/√Hz
  - 1 W, 1.06 µ Nd:YAG lasers

- **Drag-free control**
  - Positioning to 10 nm/√Hz
  - Attitude to 3 nrad/√Hz
Payload

\[(\text{Acceleration Noise} \sim 3 \times 10^{-15} \text{ (m/s}^2)/\text{Hz}^{-1/2})\]
LISA Science Capabilities
(Focus on Black Holes)
LISA Science Goals & Sources

Science Objectives:
• Determine the role of massive black holes in galaxy evolution, including the origin of seed black holes
• Make precision tests of Einstein’s Theory of Relativity
• Determine the population of ultra-compact binaries in the Galaxy
• Probe the physics of the early universe

Observational Targets:
• Merging supermassive black holes
• Merging intermediate-mass/seed black holes
• Gravitational captures by supermassive black holes
• Galactic and verification binaries
• Cosmological backgrounds
LISA Science: Massive Black Holes

- Two primary classes of BH studies
  - Extreme Mass Ratio Inspirals (EMRI)
    - Capture of stellar-mass compact object by Massive BH (e.g. $10 \, M_\odot \times 10^6 \, M_\odot$)
  - Massive Black Hole Mergers
    - Merger of 2 massive BHs following galaxy merger

- Mergers: Key Issues for detection
  - MBH mass spectrum
  - Galaxy merger rates
  - Time to merger of MBHs after galaxy merger

- Capture events: Key Issues for detection
  - Rate of capture events involving massive black holes in galactic nuclei
  - LISA detection of extreme mass ratio inspiral
Massive Black Hole Mergers
Are Massive Black Holes Common in Galactic Nuclei?

But do they merge?

D. Richstone et al., Nature 395, A14, 1998
Space Density of Not So Supermassive Black Holes?

(From Phinney et al.)
Rate Estimates for Massive Black Hole Mergers

- Use hierarchical merger trees
- Rate estimates depend on several of factors
  - In particular space density of MBHs with $M_{BH} < 10^6 M_\odot$
  - Depends on assumptions of formation of MBHs in lower mass structures at high-z
- Some recent estimates
  - Sesana et al. (2004): about 1 per month
  - Menou (2003): few to hundreds per year depending on assumptions
  - Haehnelt (2003): 0.1 to 100 per year depending on assumptions

Fig. 8.— Number of events per unit redshift interval resolved by LISA with $S/N > 5$ in $10^8$ secs. Thick-solid histogram: total number of events in $10^8$ secs. Solid histogram: number of stationary events. These events are of much longer duration compared to the mission lifetime. Dashed histogram: number of bursts in $10^8$ secs. These events are of short duration compared to the mission lifetime.

[Sesana et al, astro-ph/0401543]
Figure 1. Event rates (per year, per unit redshift) of MBH mergers in models with BHs in all (100%, a) or only 3% (b) of potential host galaxies at $z = 5$. Very efficient MBH binary coalescence is assumed. In (b), two models are shown depending on whether rare MBHs preferentially populate massive $z = 5$ galaxies (dashed) or populate them randomly (dotted). These rates are likely overestimated, as explained in the text. [From Menou et al. 2001.]

[Menou, 2003]
Do Massive BH Binaries Merge?

### Last Parsec Problem

The “Last Parsec Problem”

- **GALAXY MERGER**

\[
a_{\text{hard}} = \frac{G(M_1 + M_2)}{8\sigma^2}
\]

- **COALESCENCE**

\[
a_{\text{gr}} = \left\{ \frac{64}{5} \frac{G^3(M_1 + M_2)^3}{c^5 F(e)} l_{\text{gr}}^{\frac{1}{4}} \right\}
\]

(Adapted from Milosavljevic, ‘02)
The “Last Parsec Problem”

Note: diffusion and re-ejection are simultaneous

(Adapted from Milosavljevic, ‘02)
Can LISA Detect Massive Black Holes Mergers?

Gravitational Wave Amplitude $h$

Frequency (Hz)

$LISA$ Instrumental Threshold
1 yr, $S/N=5$

Binary Confusion Noise Threshold Estimate;
1 yr, $S/N=5$

$MBH-MBH$ Binaries at $z=1$

$\frac{a}{M} = 0$

$10^{7} M_{\odot}$

$10^{5} M_{\odot}$

$10^{4} M_{\odot}$

$10^{3} M_{\odot}$

$10^{2} M_{\odot}$

$10^{1} M_{\odot}$

$10^{0} M_{\odot}$
LISA Capabilities for Intermediate-Mass BHs

- How did the $>10^6 M_\odot$ black holes we see today arise?
  - What were the masses of the “seed” black holes?
- Do black holes exist in significant numbers in the mass range: $10^2 M_\odot < M_{BH} < 10^6 M_\odot$?
- LISA capabilities
  - Maximum frequency scales roughly inverse to mass
  - Low-mass BH mergers at high redshift can be in optimal LISA sensitivity band

![LISA Sensitivity (5\sigma)](image)

- 5\sigma detection
Summary: Massive Black Hole (MBH) Mergers

- **Science Measurements**
  - Comparison of merger, and ringdown waveforms with predictions of numerical General Relativity
  - Number of mergers vs redshift
  - Mass distribution of MBHs in merger events (masses to ~10^{-4} accuracy)
  - Spin of MBHs

- **MBH Mergers**
  - Fundamental Physics
    - Precision tests of dynamical non-linear gravity
  - Astrophysics
    - What fraction of galactic merger events result in an MBH merger?
    - When were the earliest MBH mergers?
    - How do MBHs form and evolve? Seed BHs?
Observational Evidence for Massive Black Hole Binaries?

- Several observed phenomena may be attributed to MBH binaries or mergers
  - X-shaped radio galaxies (see figure)
  - Periodicities in blazar light curves (e.g. OJ 287)
  - X-ray binary MBH: NGC 6240
- See review by Komossa [astro-ph/0306439]

[Merritt and Ekers, 2002]
Extreme Mass Ratio Inspirals
(Gravitational Capture Events)
Extreme Mass Ratio Inspiral: Key Issues

- What is the rate of compact object capture by MBH in galactic nuclei?
- How does the orbit of a compact object evolve as it spirals into a massive BH?
- What are the GW waveforms?
- Can the complex GW waveforms be detected by LISA?
- Can other backgrounds be subtracted (e.g. binary white dwarf systems)?
- How do we test GR with the ~10^5 orbits that occur during inspiral?

Typical EMRI event: 10 M_☉ BH captured by 10^6 M_☉ BH

Significant progress on several of these issues during the last year
Estimating Waveforms

Temporal and harmonic content of “Analytic Kludge” waveforms

[Barack and Cutler, 2003]
Subtracting Galactic Binary Background

- LISA will observe distinguishable signals from $\sim10^4$ binary star systems in the Galaxy + a background from an even larger population of unresolved sources
- Methods have been developed for source subtraction (e.g. gCLEAN, Cornish and Larson)
- Sensitivity estimates include effects of non-ideal background source subtraction

Monte-Carlo simulation of the gravitational-wave signals from galactic binaries with periods less than 1 hour. The right-hand plot has a linear scale for the signal amplitude; insets show expanded (in frequency) views of narrow-band regions near 3 mHz and 6 mHz. (Phinney)
Extreme Mass Ratio Inspiral Detection Estimates

- **Takes into account**
  - MBH space density estimates
  - Monte Carlo results on capture rates scaled to range of galaxies
  - Approximate waveforms
  - Subtraction of binary background
  - Computational limits in number of templates
    - Assumes multi-Teraflop computer
    - 3 week coherent segments

- **Results**
  - LISA sensitivity degraded by about x2 with respect to optimal => reduction of x10 in detection rates
  - Largest rate from stellar-mass BHs captured by $\sim 10^6$ Msol MBHs
  - Predict hundreds of inspirals over LISA lifetime

<table>
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<th>$M_\bullet$ (10^6 Msol)</th>
<th>$m$</th>
<th>LISA</th>
</tr>
</thead>
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<tr>
<td>300 000</td>
<td>0.6</td>
<td>8</td>
</tr>
<tr>
<td>300 000</td>
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<td>739</td>
</tr>
<tr>
<td>300 000</td>
<td>100</td>
<td>1*</td>
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<td>1*</td>
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</tr>
<tr>
<td>3 000 000</td>
<td>100</td>
<td>2*</td>
</tr>
</tbody>
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[Phinney et al., 2003]

Optimistic: 5 years/3 arms/ideal subtraction
Pessimistic: 3 years/2 arms/gClean subtraction
Summary: Extreme Mass Ratio Inspiral

- LISA signals expected to come primarily from low-mass (~10 $M_\odot$) BH inspiral into massive (~$10^6 M_\odot$) BH
- Potential to “map” spacetime of MBH as compact object spirals in (e.g. ~$10^5$ orbits available for mapping)
- Also measure astrophysical parameters
  - Masses, spins, distances, properties of nuclear star clusters
- Recent progress in estimating detection rates
  - Several per month are potentially detectable by LISA
    - Barack & Cutler, gr-qc/0310125
    - LISA WG1 EMRI Task Group: Barack, Creighton, Cutler, Gaier, Larson, Phinney, Thorne, Vallisneri (December, 2003)
  - Note: Capture and tidal disruption of stars may be common
    - X-ray observations suggest significant rate of compact object capture (February 2004 news article on disruption event - RX J1242.6-1119A; Komossa et al., 2004)
Summary: Physics with Massive Black Holes

- Capture and Merger events represent 2 extremes for studying BH physics
  - MBH Mergers: strong-field non-linear gravity at high SNR (>1000)
  - Captures: clean probe of MBH spacetime, low-mass BH is a small perturbation

- MBH mergers
  - Allows high-SNR comparisons with predictions of numerical relativity
  - Currently numerical relativity techniques not sufficiently advanced

- Capture events
  - Accurate mapping of BH spacetime with $10^5$ orbits
  - Distinguish between Kerr and alternate metrics (“no hair”)
  - For Kerr, all multipoles parametrized by mass MBH and spin aBH
LISA Status
LISA Flight Technology Validation

ESA will fly European and US technology packages on Pathfinder (Launch scheduled for 2008)

2 proof masses in “drag-free” environment
- Compare relative motions of 2 masses to determine disturbance level
- Aim for $3 \times 10^{-14} \text{ (m/s}^2\text{)/}\sqrt{\text{Hz}}, \text{ 1-10 mHz}$

ESA Pathfinder Spacecraft

Major Stanford role

US test package

Proof Mass Prototype
LISA Status Summary:

- Ranked by the science community as a very high-priority mission in both US and Europe
- Technology development validation flight on ESA Pathfinder spacecraft in 2008
- LISA currently planning for 2012+ launch
Backup Slides
What are Gravitational Waves?

- Analogous to electromagnetism, variations in space and time of a gravitational field cannot be felt instantaneously at a distant point. Variations of the field propagate at the speed of light through gravitational waves (GW).

- GW are related to the quadrupolar mass distribution of the source (no dipole-radiation: no negative mass)

- GW carry energy (e.g. PSR 1913+16 orbit decay & now PSR J0737-3039)

- GW couple very weakly to matter => bring information about regions of the Universe otherwise unobtainable
Gravitational Waves and the Big Bang

What Powered the Big Bang?

Gravitational Waves can Escape from Earliest Moments of the Big Bang

Big Bang plus $10^{-43}$ Seconds

Big Bang plus 300,000 Years

Inflation (Big Bang plus $10^{-35}$ seconds?)

Cosmic microwave background, distorted by seeds of structure and gravitational waves

Big Bang plus 15 Billion Years

Now
Gravitational Waves from the Early Universe

- Potentially the most fundamental discovery that LISA could make

- Universe became transparent to gravitational waves at very early times (~ $10^{-35}$ sec after the big bang)
  - Gravitational waves provide our only chance to directly observe the Universe at its earliest times
  - The cosmic microwave background (CMB) probes much later times (400,000 years after the big bang), although inflationary GW may have left a polarization imprint on the CMB
  - LISA will probe GW length and energy scales at least 15 orders of magnitude shorter and more energetic than the scales probed by CMB
  - Possibilities for relic gravitational wave emission: Non-standard inflation, phase transitions, cosmic strings?

- **LISA sensitivity**: $\Omega_{GW} \sim 10^{-11} - 10^{-10}$ (Vecchio, 2001)
  - Compare to “slow-roll” prediction in range $\Omega_{GW} \sim 10^{-16} - 10^{-15}$
Galactic Binaries

- Galactic compact binaries are a “sure source” for LISA
  - Important both for science and for instrument performance verification
- LISA will observe distinguishable signals from $\sim 10^4$ binary star systems in the Galaxy + a background from an even larger population ($10^8$) of unresolved sources
- Below $\sim 3$ mHz ($\sim 650$ second orbital period)
  - More than one binary per frequency bin for a 1 yr observation
  - Confusion noise background
- Above $\sim 3$ mHz
  - Resolved sources
  - Chirping sources for $f > 6$ mHz => mass, distance, time to merger
  - Several known binaries (e.g. AM CVn) will be detected
- LISA will allow construction of a complete map of compact galactic binaries in the galaxy
- Studies include structure of WDs, interior magnetic fields, mass transfer in close WD systems, binary star formation history of galaxy
Comparisons by $z$ and mass
LISA Interferometry

- “LISA is essentially a Michelson Interferometer in Space”
- However
  - No beam splitter
  - No end mirrors
  - Arm lengths are not equal
  - Arm lengths change continuously
  - Light travel time ~17 seconds
  - Constellation is rotating and translating in space
Time Delay Interferometry (TDI)

- Intrinsic phase noise of laser must be canceled by a factor of up to $10^9$ in amplitude
- Because the arm lengths are not equal, the laser phase noise will not cancel as it does in an equal-arm Michelson
- Solution: record beat signal of each received laser beam relative to an onboard reference. Delay recorded signals relative to each other and subtract in proper (TDI) combinations.
Comparisons by $z$ and mass
Determining Polarization

- LISA has 3 arms and thus can measure both polarizations

\[
\frac{\delta (L_3 - L_1)}{L} = \frac{\sqrt{3}}{4} \left( H_{XX} - H_{YY} \right) = \frac{\sqrt{3}}{2} h_+ \\
\frac{\delta (2L_2 - L_3 - L_1)}{L} = \frac{\sqrt{3}}{4} \left( H_{XY} - H_{YX} \right) = \frac{\sqrt{3}}{2} h_-
\]

- Gram-Schmidt orthogonalization of combinations that eliminate laser frequency noise yield polarization modes
  - Paper by Prince et al. (2002)
    - gr-qc/0209039

(notation from Cutler,Phinney)
“What is Dark Energy”?

- Can LISA use black hole mergers to probe dark energy?
- A unique feature of gravitational wave astronomy is that most sources are “standard candles” with accurate distances (1%)
- If even ~10^{-20} of the merger energy is emitted as photons, the merger may be detectable with telescopes, the host galaxy identified, and a redshift measured (as for GRBs)
- A few black hole mergers observed with LISA might measure dark energy about as well as the proposed JDEM/SNAP mission if the redshifts of the host galaxies could be determined (and if lensing is ignored)
- Weak lensing will likely determine the ultimate limit for dark energy measurements using BH mergers (requires further calculations, see e.g. Holz and others)
Massive Black Hole Mergers: SNR

Cumulative Signal to Noise Ratio

MBH-MBH Binaries at z=1; Sum of Binary Confusion Noise Estimate plus LISA Instrumental Noise

\[ \frac{a}{M} = 0 \]

S/N = 5