Astronomy and Physics with LISA:
Opening a New Window on the Universe

Tom Prince
US LISA Mission Scientist
Caltech/JPL

http://lisa.nasa.gov
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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:
- Characteristics of gravitational waves and gravitational wave sources
- LISA mission concept
- LISA science capabilities
- LISA status

Gravitational Waves

Two polarizations of GWs

Laser interferometer

\[ h = \frac{\Delta L}{L} \]

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

How big might $h$ be for a typical LISA source?

- Use Newtonian/quadrupole approximation to Einstein Field Equations:
  $$h = \frac{\Delta L}{L} \sim \left( \frac{G}{c^4} \right) \frac{\ddot{Q}}{r}$$  
  \[ \ddot{Q} \text{ is the second time derivative of the source mass quadrupole} \]
  $$h \sim \frac{1}{c^2} \frac{4G(E_{\text{kin, non-sphere}}/c^2)}{r} \sim \frac{4GM_{\text{equiv}}}{rc^2}$$

- 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

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

  (Compare to typical $10^{-21}$ to $10^{-23}$ sensitivity of LISA)

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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
This Talk:

- Characteristics of gravitational waves and gravitational wave sources
  - LISA mission concept
- LISA science capabilities
- LISA status
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

![Orbit Diagram]

\[1 \text{ AU} = 1.5 \times 10^8 \text{ km}\]

Determining Source Directions

- Directions (to about 1 degree): 2 methods: AM & FM
- FM: Frequency modulation due to LISA orbital doppler shifts
  - Analogous to pulsar timing over 1 year to get positions
  - 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 \( f < 1 \text{ mHz} \)
- 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)

![Source Direction Diagram]

(Cornish and Larson, ‘01)
Determining Source Distances

- Distances (to about 1%)
- Binary systems with orbital evolution (df/dt)
  - “Chirping” sources
  - Determine the luminosity distance to the system by comparing amplitude, $h$, and period derivative, $df/dt$, of the gravitational wave emission
  - Quadrupole approximation:
    $$ h \propto \frac{M_{\text{Chirp}}^{5/3}}{D_L} f^{2/3} $$
    $$ f \propto M_{\text{Chirp}}^{5/3} f^{11/3} $$
- Luminosity distance ($D_L$) can be estimated directly from the detected waveform
- See e.g. work by Hughes, Vecchio for quantitative estimates

Determining Polarization

- LISA has 3 arms and thus can measure both polarizations

$$ \frac{\delta (L_1 - L_2)}{L} = \frac{\sqrt{3}}{4} (H_{XX} - H_{YY}) = \frac{\sqrt{3}}{2} h_+ $$
$$ \frac{\delta (2L_2 - L_3 - L_4)}{L} = \frac{\sqrt{3}}{4} (H_{XY} - H_{YX}) = \frac{\sqrt{3}}{2} h_\times $$

- 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)
LISA Sensitivity

2-arm "Michelson" sensitivity \( \left( h = \sqrt{T_{obs}} \right) \)

- **Frequency**
  - 0.1 mHz
  - 1 Hz

(Sources include gravitational wave transfer function averaged over sky position and polarization. Source sensitivities plotted as \( h = \sqrt{T_{obs}} \).)

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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
LISA Interferometry

- “LISA is essentially a Michelson Interferometer in Space”
- However
  - No beam splitter
  - No end mirrors
  - Arm lengths are not equal
    (as much as 10,000 km difference)
  - Arm lengths change continuously
    (1 m/s)
  - 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.
LISA Science: Massive Black Holes

- Two primary classes of BH studies
  - Massive Black Hole Mergers
    - Merger of 2 massive BHs following galaxy merger
    - Merger of Intermediate Mass BH (IMBH) with SuperMassive BH (SMBH)
  - Extreme Mass Ratio Inspirals (EMRI)
    - Capture of stellar-mass compact object by Massive BH (e.g. 10 M_⊙x10^8 M_⊙)

- Mergers: Key Issues for detection
  - MBH mass spectrum (IMBH and SMBH)
  - Galaxy merger rates

- Capture events: Key Issues for detection
  - Rate of capture events involving massive black holes in galactic nuclei
  - LISA detection of extreme mass ratio inspiral

1) Massive Black Hole Mergers
Are Massive Black Holes Common in Galactic Nuclei?

BH Mass vrs Bulge Velocity Dispersion

\[ M_\bullet (M_\odot) \]

\[ \sigma \ (\text{km/s}) \]

\[ 10^6 \]

\[ 10^7 \]

\[ 10^8 \]

\[ 10^9 \]

\[ 50 \]

\[ 100 \]

\[ 200 \]

\[ (\text{Kormendy & Gebhardt, 01}) \]

But do they merge?

Do Massive BH Binaries Merge?

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

The "Final Parsec Problem"

\[ a_{\text{gr}} = \left[ \frac{64 G(M_1 + M_2)^2}{c^3 F(e)} \right]^{1/3} \]

(Adapted from Milosavljevic, '02)
Dr. Tom Prince, Caltech & KITP (KITP 10-21-04) The Laser Interferometer Space Antenna: Mission Concept and Capabilities.

The “Last Parsec Problem”

- power-law
- core

binary’s semi-major axis (parsec)

GALAXY MERGER
- hard binary
- super-hard binary
- re-ejection
- re-ejection
- diffusion and re-ejection are simultaneous
- non-equilibrium enhancement

black hole mass (solar mass)

COALESCENCE

(Adapted from Milosavljevic, ‘02)

Rate Estimates for Massive Black Hole Mergers

- Use hierarchical merger trees
- Rate estimates depend on several 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. **Solid histogram:** total number of events in $10^8$ secs. **Thick-solid histogram:** total 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]
Can LISA Detect Massive Black Holes Mergers?

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 $10^2 M_\odot < M_{BH} < 10^4 M_\odot$?
- Maximum frequency scales roughly inverse to mass
- Intermediate-mass BH mergers at high redshift can be in optimal LISA sensitivity band

LISA Sensitivity ($5\sigma$)

Binary Coalescence:
- MBH-MBH
- MBH-SMBH
- SMBH-SMBH

MBH-MBH Binaries at z=1
- 1/5p SNR
- 1/5p SNR
Summary: Massive Black Hole (MBH) Mergers

- Science Measurements
  - Comparison of merger, and ringdown waveforms with predictions of numerical General Relativity
  - Number of mergers vs distance
  - Mass distribution of MBHs in merger events (masses to $\sim 10^{-4}$ 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?

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2) 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 $\sim 10^5$ orbits that occur during inspiral?

Significant progress on many of these issues during the last year

Estimating Waveforms

Temporal and harmonic content of approximate waveforms

[Barack and Cutler, 2003]
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>
<thead>
<tr>
<th>$M_\bullet$ (Msol)</th>
<th>$m$</th>
<th>LISA Optimistic</th>
<th>LISA Pessimistic</th>
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<tr>
<td>300 000</td>
<td>0.6</td>
<td>8</td>
<td>0.7</td>
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<tr>
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<td>10</td>
<td>739</td>
<td>89</td>
</tr>
<tr>
<td>300 000</td>
<td>100</td>
<td>1*</td>
<td>1*</td>
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<tr>
<td>1 000 000</td>
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<td>94</td>
<td>9</td>
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<td>10</td>
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<td>1*</td>
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<tr>
<td>3 000 000</td>
<td>100</td>
<td>2*</td>
<td>1*</td>
</tr>
</tbody>
</table>

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 ($\sim 10 M_\odot$) BH inspiral into massive ($\sim 10^6 M_\odot$) BH
- Potential to “map” spacetime of MBH as compact object spirals in (e.g. $\sim 10^5$ orbits available for mapping)
- Study properties of nuclear BHs and their associated star clusters
  - Masses, spins, distances, population 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)
3) Ultra-Compact Binaries in the Galaxy

LISA will observe distinguishable signals from \(10^4\) binary star systems in the Galaxy, a background from an even larger population of unresolved sources.
Formation Scenarios for ultra-compact binaries

- Observationally seen as LMXBs or AM CVn systems
- Evolution through common envelope phase(s), but progenitors and evolutionary paths still uncertain
- Several possible progenitors/scenarios
  - White dwarf secondary + (wd, ns, or bh)
  - Semi-degenerate He star + (wd, ns, or bh)
  - CVs with evolved donors
- Systems observed via mass transfer
  - White dwarf primary (AM CVn systems)
  - NS or BH primary (ultra-compact X-ray binary)

Mass-transfer Binaries

LISA will detect binaries with and w/o mass transfer

(From Nelemans, ’03)
### Estimate of systems observable with LISA

- **Estimate from Nelemans et al**

<table>
<thead>
<tr>
<th>Change</th>
<th>Mass Xfer?</th>
<th>Resolved</th>
<th>Frequency</th>
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<td>(wd,wd)</td>
<td>No</td>
<td>12163</td>
<td>560</td>
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<tr>
<td>AM CVn</td>
<td>Yes</td>
<td>10117</td>
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<tr>
<td>Compact XRB</td>
<td>Yes</td>
<td>37</td>
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<tr>
<td>(ns,wd)</td>
<td>No</td>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>(ns,ns)</td>
<td>No</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(bh,wd)</td>
<td>No</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(bh,ns)</td>
<td>No</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

( ) = detached

### Summary: Ultra-compact Binary Studies with LISA

- LISA will observe over 10,000 individual compact binaries
  - Explore evolutionary pathways in considerable detail
  - Large sample of both detached systems & Roche-lobe filling
- LISA will observe a frequency derivative (fdot) for the few thousand highest frequency binaries
  - Get chirp masses and distances (plus period, inclination, etc.)
  - 3D obscuration-free map of galaxy (LISA will see all such sources)
  - New types of sources, e.g.
    - WDs with strong internal magnetic fields
    - WDs with tidal excitation and dissipation

LISA will allow construction of a complete 3-D map of the close binary systems in the galaxy.
Summary: LISA Capabilities for BH & Compact Binary Studies

- **Mergers of supermassive and intermediate mass BHs**
  - Expect order (10’s) of source detections
  - No distance limit for BHs with mass > $10^5 M_{\odot}$
  - Observe for typically few months

- **Extreme mass ratio inspiral**
  - Expect order (100’s) of source detections
  - Precise tests of GR over $10^5$ phase-connected orbits

- **Compact binaries**
  - Expect order (10,000’s) of source detections
  - Complete 3D map of all galactic ultra-compact binaries

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4) GW from the Early Universe
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^−35 seconds: Cosmic microwave background, distorted by seeds of structure and gravitational waves

Big Bang plus 10^−5 seconds: Light

Big Bang plus 300,000 years: Gravitational waves

Big Bang plus 15 billion years: Now

Diagram showing cosmological parameters and models.
Gravitational Waves from the Early Universe

- Universe became transparent to gravitational waves at very early times ($\sim 10^{-35}$ 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 $\Omega_{GW} \sim 10^{-16} - 10^{-15}$

LISA: Opening a New Window on the Universe

- LISA Status Summary:
  - Ranked by the science community as a very high-priority mission in both US and Europe
  - Started Formulation (Phase A) on October 1 as part of the "Beyond Einstein" program
  - Technology development validation flight on ESA Smart-II spacecraft in 2008
  - LISA currently planning for 2012+ launch