Gravitational Wave Astronomy from Space

Tom Prince
Caltech/JPL

LISA
Laser Interferometer Space Antenna

http://lisa.nasa.gov
The Importance of Gravitational Wave Astronomy from Space

Recent NRC Review of the NASA Beyond Einstein Program
(BEPAC Report Released in September)

The Committee ranked LISA highest scientifically:

“On purely scientific grounds LISA is the mission that is the most promising and least scientifically risky … Thus, the committee gave LISA its highest scientific ranking”

This Briefing:

The Promise of Gravitational Wave Astronomy
EM Counterparts
The LISA Mission

(Brief Remarks on Long-term Future)
THE GRAVITATIONAL WAVE SPECTRUM

**Sources**

- Quantum fluctuations in the very early Universe
- Binary supermassive black holes in galactic nuclei
- Phase transitions in the early universe
- Black holes, compact stars captured by supermassive holes in galactic nuclei
- Binary stars in the galaxy and beyond
- Merging binary neutron stars and stellar black holes in distant galaxies; fast pulsars with mountains

**Age of the Universe**

- **Wave Period**
  - 10^{-16}
  - 10^{-14}
  - 10^{-12}
  - 10^{-10}
  - 10^{-8}
  - 10^{-6}
  - 10^{-4}
  - 10^{-2}
  - 1
  - 10^2

**Frequency (Hz)**

- **Detectors**
  - Inflation Probe (NASA)
  - Precision timing of millisecond pulsars (1982 - )
  - LISA (ESA/NASA, 2010)
  - Big Bang Obs (NASA)
  - GEO, LIGO, VIRGO, TAM (2002 - )
  - Laser interferometers on Earth (also bar detectors)
Many Strong Signals at Low Frequencies

LISA signals record a richly populated universe of strong sources

- Massive Black Hole Binary (BHB) inspiral and merger (~hundreds)
- Ultra-compact binaries (~thousands)
- Capture of stellar-mass Black Holes by massive BHs in normal galactic nuclei (~hundreds)
- Cosmic backgrounds, superstring bursts, …?
Why are Gravitational Waves (GW) Excellent Probes of Physics & Astrophysics?

GW are not attenuated

Universe transparent since about $10^{-34}$ sec

GW sources are “standard candles”

Luminosity distance measurements with 1% accuracy

GW sources are “clean and simple”

Black Holes have mass and spin and radiate coherently

GW sources are strong

High signal-to-noise allows precision measurements
LISA sources have very large signals

Merger signals have high SNR even in a single wave cycle

Simulated LISA data stream at merger event, two $10^5 M_\odot$ BH at $z=5$ including simulated noise (S/N~500)
LISA sources have very large signals

* Merger signals have high SNR even in a single wave cycle *

Simulated LISA data stream at merger event, two $10^5M_\odot$ BH at $z=15$ including simulated noise

(Baker et al. 2006)
LISA: Precision Measurements of Simple Systems

High SNR waveforms carry precision information about the emitting systems.

High-precision black hole properties from LISA measurements:

- Massive black hole mergers: Masses, spins to <0.1%, distances to 1% or less (z=1; an order of magnitude worse at z=20)
- Extreme mass ratio inspirals: Spins to 0.01%, distances to 1% (z<1)
- Masses, spins, and numbers as a function of redshift: How did black holes (BHs) initially form and what were their masses? How did accretion spin-up the BHs? How do the spins evolve over time? What happened to BHs as the initial galaxies merged to make modern galaxies.
BH Mergers: Nodes on Merger Trees

- Supermassive BH evolution includes mergers of many (10’s) of smaller BHs
- LISA will detect the mergers of moderate mass BH’s ($10^4 M_\odot - 10^7 M_\odot$)
- LISA can detect BH mergers out to $z=20$
- Mass, spin, distance well-measured

- Di Matteo et al (2007) simulation
- Merger tree evolution of most massive BH at $z=1$
Massive Binary Black Holes: strong signals

Contours of SNR, equal mass merger (optimal)

(Baker et al. 2006)
Massive Binary Black Holes: strong signals

High SNR needed for mass, spin, distance
Absolute Distances from Black Hole Binaries

Waveforms of black hole binaries give precise, gravitationally calibrated distances to high redshift.

Absolute luminosity distances can be derived directly from

- amplitude
- orbital frequency
- chirp time

\[
\text{Distance} \approx c \frac{1}{\text{frequency}^2 \times t_{\text{chirp}} \times \text{amplitude}}
\]

1. Distances accurate to 0.1% to ~10% per event
2. Absolute, physical calibration using only gravitational physics
Absolute Distances: Hubble Constant and Dark Energy

- ~10’s of events expected to z~3; 100’s to z~20
- Cosmological distance requires redshift (either host identification or statistical)
- Noise from weak lensing
- Comparable precision to weak lensing, baryon acoustic oscillations, clusters, and supernovae techniques
- **Absolute & Independent** measurement

\( H_0 \) and Dark Energy parameters potentially measured to <1%
“LISA also has the potential to measure the dark energy equation of state, along with the Hubble constant and other cosmological parameters. Through gravitational wave form measurements LISA can determine the luminosity distance of sources directly. If any of these sources can be detected and identified as infrared, optical or x-ray transients and if their redshift can be measured, this would revolutionize cosmography by determining the distance scale of the universe in a precise, calibration-free measurement.” (NRC BEPAC)
Will We See Electromagnetic Signals from BH mergers?

- Not guaranteed, but if detected yields exciting scientific return
- Host galaxy identification provides unique information on galaxy-BH co-evolution
- Host galaxy identification allows precision determination of distance-redshift relation
- LISA will provide few-degree error boxes and time of merger months before merger
- Error boxes shrink to degree or sub-degree size as signal-to-noise increases and merger approaches

The first LISA detections of massive Black Hole mergers will mobilize global astronomical resources and be an astronomical event of enormous excitement. These are the most energetic events in the universe since the Big Bang.
Electromagnetic Signals from BH mergers?

Stages in the evolution of a disk of gas around a binary black hole.

- **decoupling**
  - $t_{\text{visc}} \leq t_{\text{gr}}$
  - Black holes inspiral via gravitational radiation. Hollow circumbinary disk follows them in.

- **BH merger**
  - $t_{\text{visc}} > t_{\text{gr}}$
  - GW inspiral time becomes too fast for viscous disk to follow. “Frozen disk”. Waves previously induced by binary decay on disk’s radiative time.
  - Dynamical response of disk, disk oscillations and shocks. X-ray, UV, optical, IR variability on minutes-days after merger.

- **Afterglow**
  - Viscosity fills in disk. Accretion starts, X-ray, UV AGN turns on.

\[ t_d = -0.25 t_{sh} \quad \bullet \quad t_m = 0 \quad \bullet \quad t_{on} = 0.75 t_{sh} \]

\[ t_{sh} = 1 - 10 \, \text{yr for } 10^5 M_\odot \text{ black hole} \]

Macfadyen & Milosavljevic 2006 astro-ph/0607467


Dotti et al 2006 MNRAS 372, 869

E.S. Phinney Caltech 8 Oct 2007
LISA - Laser Interferometer Space Antenna

- **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.

- **Status (Nov 2007)**
  - Currently undertaking joint ESA-NASA formulation studies.
  - Overall system architecture and performance requirements basically stable for almost a decade.
  - Technology development continuing, including LISA Pathfinder flight in 2010.
  - Preparing for Decadal Review (US) and Cosmic Vision selection (Europe).
LISA Optics & Metrology

- **Components**
  - 1 W lasers (Nd:YAG)
  - 30 cm telescopes
  - Drag-free proof masses

- **Measurements**
  - 6 laser Doppler signals between S/C
  - 6 reference beams between S/C assemblies
ESA is developing a mission to validate LISA flight subsystems with launch scheduled for 2010.

Engineering models exist for all major LISA Pathfinder sub-systems: proof masses, optical bench, lasers, thrusters, etc. Flight articles being fabricated.
Launch in 2010 for SELECTED ORBIT: L1
LISA Readiness for Implementation

- All technologies on track to achieve TRL 6 status
  - Independent technology reviews
  - Most recently, BEPAC

- LISA Pathfinder development and flight retiring significant risk factors
  - Caging mechanisms
  - Gravitational reference system (also ground torsion balance testing)
  - Drag free control
  - Micro-thruster and laser lifetime are key areas requiring additional ground testing

- BEPAC recommendation
  - LISA ready to proceed after LISA Pathfinder has successfully flown (2010)
Summary

- LISA rated very highly scientifically
- Very broad physics and astrophysics reach
  - Black hole/galaxy evolution - spins, masses, distances
  - End points of stellar evolution - complete census of ultra-compact binaries in the Galaxy
  - Masses, spins of BHs at z<1 (extreme mass ratio inspirals)
  - Conditions in vicinity of BHs in normal galactic nuclei (extreme mass ratio inspirals)
  - Precision cosmography (possible dark energy, $H_0$ measurement)
  - Precision tests of General Relativity
  - New physics discovery potential (cosmic strings, early universe phase transitions)
  - The unexpected (this is a new window on the Universe!)
- LISA ready to finish formulation and proceed to implementation
- Gravitational wave astronomy has huge potential for 2020 and beyond