The Science of Gravitational Waves with Space Observatories

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Talk Outline

I. Gravitational Waves - What, Where, Why, & How?
II. The “classic” LISA mission
III. Science with LISA
IV. Current concepts & opportunities
Gravitational Waves

what?
where?
how?
why?
What are Gravitational Waves?

Dynamical part of spacetime

- Wave solutions to vacuum Einstein equations
- Curvature perturbations to background metric
- Propagate at the speed of light
- Carry energy & momentum
- Have two polarizations
Where do they come from?

Compact objects in binaries

Formation of compact objects

- large masses
- high velocities
- small volumes

Big Bang

Cosmic Strings?

L_{GW} \propto \frac{M^2 v^6}{r^2}
Binary inspirals & merger

Early Inspiral

- GWs carry away energy
- Adiabatic shrinking of the binary
- Analytically tractable

\[ a(t) = a_0 \left(1 - t/\tau\right)^{1/4} \]

Late Inspiral

- Exponential increase in L
- More complex physics
  - GR orbital effects
  - Tides & mass-transfer

Merger

- Merger of compact object(s)
- Formation of new object
- Physics more difficult
Detecting Gravitational Waves

- Oscillating tidal distortions
- Displacement scales with separation
- Two polarizations

\[ h \equiv \frac{\delta L}{L} \propto \frac{G^2}{c^4} \frac{1}{D} \frac{M^2}{r} \]

Small amplitudes

Linear in source distance

\[ h \sim 10^{-21} \]

Dia. of H atom

Astronomical Unit

Earth

Sun
The Gravitational Wave Spectrum

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period

age of universe

years

hours

sec

ms

log(f)

-16

-14

-12

-10

-6

-4

-2

0

+2

Detectors

Cosmic microwave background polarization

Pulsar Timing

Space Interferometers

Terrestrial interferometers

This Talk
Welcome to the jungle...
Seeing and Hearing the Universe

Electromagnetic Waves
- Tell us about atoms & molecules
- Often absorbed/modified in transit
- Hard to determine distance
- Easy to determine sky location
- Easy to measure redshift

Gravitational Waves
- Tell us about (large) masses
- Travel directly to us
- Easy to determine distance
- Hard to determine sky location
- Impossible to measure redshift
LISA
LISA Mission Concept

Triangular constellation of three identical spacecraft.

Passively-stable, Earth-trailing heliocentric orbit.

(Arm length = 5 Mkm)

Drag-free flight to realize ‘freely-falling’ test mass

Heterodyne interferometry distance measurements

\[ \delta a \sim 3 \text{ fm/s}^2/\sqrt{\text{Hz}} \]

\[ \delta x \sim 10 \text{ pm}/\sqrt{\text{Hz}} \]
LISA Sources

(S)MBH binaries
~30 yr$^{-1}$

(S)MBH capture of BHs
~10$^2$ yr$^{-1}$

Close binaries in Milky Way
~10$^6$-$^7$ total, ~10$^4$ resolved

Ununknowns?
Structure Formation & Galaxy Evolution

Current Picture

- galaxies formed hierarchically
- central black holes ‘track’ galaxy mass

Open questions

- seed BH population
- BH growth (merger vs. accretion)
- BH merger rate (‘stalled’ binaries?)

GW approach

- measure statistical sample of merging binaries
- compare mass/mass ratios/spins vs. distance with model predictions

strain vs. distance

\[ M_1, M_2, \chi_1, \chi_2, D_L \ldots \]
Powerful events

SN Ia
$L_{\text{peak}} \sim 10^{43} \text{ erg/s}$

GRB
$L_{\text{peak}} \sim 10^{53} \text{ erg/s}$

BH-BH merger
$L_{\text{peak}} \sim 10^{56} \text{ erg/s}$

Detectable to high redshift

Precision parameter estimation
Cosmology with ‘Standard Sirens’

Binary merger waveform *directly* encodes luminosity distance

• intrinsic error < 0.1%
• weak-lensing limits ~3%

EM counterpart provides redshift

• identify host galaxy
• 3D error box + merger time

Lower statistics but different systematics than SN approach
Extreme Mass Ratio Inspirals

Capture of stellar-remnant BH by central BH.

Complex, long-lived orbits

- ~$10^5$ cycles measured: precision parameter estimation!
- Need templates & search strategy

Tests of GR

- small BH acts as “indestructible” test particle mapping out spacetime of large BH.
Binaries in our backyard

‘Ultra-compact’ binaries with WD, NS, or BH members

- \( \sim 10^6 \) in our galaxy within LISA band.
- \( \sim 10^4 \) resolvable
- \( \sim 10 \) already known
- Detectable in LMC, SMC and (possibly) nearby galaxies

Science applications

- compact object demographics
- binary physics (mass transfer)
- fundamental physics
- galactic structure
- globular clusters
An astrophysical laboratory for gravity research

Binary (S)MBH merger

- Compare observed waveforms with templates
- Modal analysis of ring-down

\[ (M, \chi)_1 \neq (M, \chi)_2 \]

EMRIs

- Map geodesics & compare with Kerr metric

Galactic Binaries

- Compare EM & GW signals to constrain graviton mass

See Living Reviews Article arXiv:1212.5575 [gr-qc]
Discovery Space

‘Exotic’ physics

- Inflation (certain models)
- cosmic strings
- vacuum bubble nucleation
- electroweak physics
- branes

‘Exotic’ Astrophysics

- Intermediate-mass black holes

Unexpected sources
Current Landscape
Science impact of design choices

- Instrument choices affect instantaneous sensitivity (spectral response)
- Constellation configuration & orbit affect wavefront measurement (parameter estimation or ‘imaging’)
- Mission duration affects statistics & science associated with rare events
- Each of these affect mission cost
LISA Pathfinder

- Technology demonstrator for space-based GW detectors
- ESA lead, NASA-supplied thrusters & control laws
- Validate a physics-based model for disturbance reduction
- Late stages of integration & test, launch anticipated by 2015
European Outlook

ESA call for Cosmic Visions L2 & L3 ‘Science Themes’

- Whitepapers due May 24th
- Theme Selection Nov. 2013
- Launches in 2028 & 2034
- International partnership at ~20%

eLISA Consortium (http://www.elisa-ngo.org/) organized to respond

- Will use 2-arm eLISA/NGO concept as strawman for whitepapers
- Refining science case
- Negotiating national roles & responsibilities
- Pursuing technology development
US outlook

2011-2012 NASA Mission Concept Study

- Explore trade space of science, cost, and risk
- Community input + analysis + synthesis
- Findings (my interpretation):
  - LISA-like missions have an appropriate balance of science, cost, and risk
  - Viable missions are all over ~$1B

Opportunities

- Minority partner in European mission
- Facility class mission (w/ or w/o partners) in the next decade
- Need to prepare science and technology for both possibilities
It’s a Long Road...

Ground-based detectors

2016?

Space-based detectors

2028?

Pulsar timing arrays

2020?