Gravitational Wave Astronomy I

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on behalf of the
LIGO Scientific Collaboration
http://www.ligo.org

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LIGO-G060513-00-Z
New windows

Visible

Infrared

COBE

γ-ray

GRBs

GWs ???
Challenges for a young field

- **First direct detection of gravitational waves**
  - Detection possible with existing detectors
  - Probable with upgrades to existing facilities, and/or near-future new ones

- **Transition to a field of observational astronomy**
  - EM emission – incoherent superposition of many emitters
  - Gravitational wave (GW) emission – coherently produced by bulk motions of matter
  - Matter is largely transparent to gravitational waves
    - Makes them hard to detect
    - Makes them a good probe of previously undetectable phenomena, e.g. dynamics of supernovae, black hole and neutron star mergers
  - Gravitational wave detectors are naturally all-sky devices; “pointing” can be done later in software
Overview

• **Day 1 : Introduction. Sources. Detectors.**
  » An introduction to gravitational wave astronomy
  » What are gravitational waves
  » Sources
  » Brief survey of detectors: bars, ground-based interferometers (each with one or two highlights), LISA

• **Day 2 : Ground-based interferometry**
  » Interferometric detectors
    – LIGO, GEO, Virgo
  » Some topics in commissioning: the path to design sensitivity
  » Science mode running with LIGO, GEO and TAMA

• **Day 3 : Data analysis. Future detectors.**
  » Search methods
  » Analyses from science runs for inspiral, burst, stochastic and continuous wave sources
  » Advanced LIGO
Gravitational waves

- GWs are “ripples in spacetime”: rapidly moving masses generate fluctuations in spacetime curvature:
  - They are expected to propagate at the speed of light
  - They stretch and squeeze space

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]
The two polarizations: the gravitational waveforms

- The fields are described by 2 independent polarizations: $h_+(t)$ and $h_\times(t)$
- The waveforms carry detailed information about astrophysical sources
- With gravitational wave detectors one observes (a combination of) $h_+(t)$ and $h_\times(t)$
What is the observable effect?

Example:
- Ring of test masses responding to wave propagating along z

Amplitude parameterized by (tiny) dimensionless strain $h$:

$$ h(t) = \frac{\delta L(t)}{L} $$
Why look for gravitational radiation?

• “Because it’s there!”
  » George Mallory upon being asked, “why climb Everest?”

• Test General Relativity:
  » Quadrupolar radiation? Travels at speed of light?
  » Unique probe of strong-field gravity

• Gain different view of Universe:
  » Sources cannot be obscured by dust / stellar envelopes
  » Detectable sources some of the most interesting, least understood in the Universe
  » Opens up entirely new non-electromagnetic spectrum.
  » May find something unexpected
Orbital decay: strong indirect evidence

Neutron Binary System – Hulse & Taylor
PSR 1913 + 16 -- Timing of pulsars

Neutron Binary System
• separated by ~2x10^6 km
• m_1 = 1.44m_☉; m_2 = 1.39m_☉; ε = 0.617

Prediction from general relativity
• spiral in by 3 mm/orbit
• rate of change orbital period

Emission of gravitational waves

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

Orbital decay: strong indirect evidence

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**Emission of gravitational waves**

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

~ 8 hr

**Neutron Binary System**
- separated by $\sim 2 \times 10^6$ km
- $m_1 = 1.44 m_\odot; m_2 = 1.39 m_\odot; \varepsilon = 0.617$

**Prediction from general relativity**
- spiral in by 3 mm/orbit
- rate of change orbital period

See “Tests of General Relativity from Timing the Double Pulsar” Science Express, Sep 14 2006

The only double-pulsar system known, PSR J0737-3039A/B provides an update to this result. Orbital parameters of the double-pulsar system agree with those predicted by GR to 0.05%
Aside: some terminology

Beam patterns

\[ \frac{\delta L(t)}{L} = h(t) = F^+ h_+(t) + F^x h_x(t) \]

- \( F^+, F^x : [-1, 1] \)
- \( F = F(t; \alpha, \delta) \)

LIGO example:

Strain noise curves

LIGO-G060513-00-Z
Aside: some terminology

Beam patterns

$$\frac{\delta L(t)}{L} = h(t) = F^+ h_+ (t) + F^x h_\times (t)$$

- $F^+, F^x : [-1, 1]$
- $F = F(t; \alpha, \delta)$

Strain noise curves

Strain Sensitivities for the LIGO Interferometers

Best Performance for S4

LIGO-G050230-02-E

\( h_0, 1 \text{ Sqrt[Hz]} \)

Frequency [Hz]

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Sources

- **Very high** \((10^4 \text{Hz} \leq f \leq 10^5 \text{Hz})\) gravitational waves
  - Few sources expected, but, for example: neutron star oscillations
  - Ground-based interferometers sensitive not only in low-\(f\) (near-DC) audio band, but again in higher bands (e.g. LIGO ~37kHz, ~74kHz)

- **High** \((1 \text{Hz} \leq f \leq 10^4 \text{Hz})\) gravitational waves (audio band)
  - Continuous waves: spinning compact objects
  - Binary neutron star and black hole coalescences
  - Burst events
  - Stochastic backgrounds

- **Low** \((10^{-5} \text{Hz} \leq f \leq 1 \text{Hz})\) gravitational waves
  - Continuous waves: binary compact objects
  - Binary-black hole coalescences
  - Stochastic backgrounds

- **Very low** \((10^{-9} \text{Hz} \leq f \leq 10^{-7} \text{Hz})\) gravitational waves
  - Stochastic sources: pulsar timing yields best observational limit on stochastic background

- **Ultra low** \((10^{-18} \text{Hz} \leq f \leq 10^{-13} \text{Hz})\) gravitational waves
  - Stochastic sources: polarization of CMB yields limit
Continuous Waves

- Waves from a single compact object such as a neutron or strange star (with a mountain, or precession, or with dynamic modes) in our galaxy
- Results in nearly-sinusoidal continuous gravitational waves
- Signal is doppler modulated by relative motion of star and detector, and amplitude modulated by beam pattern of detectors
- Known radio pulsars, either isolated or in binary systems
- Known x-ray neutron stars, or x-ray pulsars, LMXBs
- Unknown neutron stars – all sky, blind searches
Inspiral and merger of Black Holes and Neutron Stars

NS-NS waveforms are well described
BH-BH need better waveforms

Significant theoretical advances in simulation of BHBH mergers, see:
Pretorius, 2005;
Baker et al, 2005;
Campanelli et al, 2005
Bursts sources

• Sources emitting short transients of gravitational radiation
  » Supernovae core-collapse
  » BBH, BNS mergers
  » Black hole normal modes
  » Neutron star instabilities
  » Cosmic string cusps and kinks
  » The unexpected!

• What we know about them …
  » Catastrophic astrophysical events observed in the particle and/or electromagnetic sector will plausibly be accompanied by short signals in the gravitational wave sector \[\textit{plausible suspects}\]
  » Exact waveforms are not or poorly modeled
  » Durations from few millisecond to \(\times100\) millisecond durations with enough power in the instruments sensitive band (100-few KHz)
  » Searches tailored to the \[\textit{plausible suspects}\] “triggered searches”
  » …or aimed to the all-sky, all-times blind search for the unknown using minimal assumption on the source and waveform morphology \[\textit{untriggered}\] “untriggered” searches

• Multi-detector analyses are of paramount importance
Stochastic sources and limits

Characterized by log-frequency spectrum:

$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d\ln f}$$
Low frequency sources

• Low frequency \((10^{-5} \text{Hz} \leq f \leq 1\text{Hz})\) sources are thought to be guaranteed
• Majority are long-lived
• One year of LISA data contains:
  » A dozen of known solar mass binaries (verification sources)
  » \(\sim 10000\) white dwarf binaries (a few with NS companion)
  » \(\sim 100\) extreme mass-ratio inspirals
  » \(\sim 10\) massive BH binaries
  » Some short lived burst events
  » Stochastic foregrounds and backgrounds

\(t \ll t_{\text{merge}}\)

Binary black hole 3C 75
Credit: NASA/CXC/Hudson et al.
NRAO/VLA/NRL
Gravitational wave spectrum

- Low frequency
  - Coalescence of Massive Black Holes
  - Resolved Galactic Binaries
  - Unresolved Galactic Binaries

- High frequency
  - NS-NS and BH-BH Coalescence
  - SN Core Collapse
  - Rotating Neutron Stars

Frequency [Hz]

Gravitational Wave Amplitude

Logarithmic scale from $10^{-24}$ to $10^{-18}$
First efforts for direct detection

- Pioneered by Joseph Weber in the early 1960’s
- Room temperature in-vacuum resonant mass detectors
- Piezoelectric strain gauges at center of bar
- Narrow band instruments with sensitivity near 1kHz
- Looked for coincident burst events with detectors in Washington D.C. and Chicago
- Controversy in detection claims that have not be verified in follow up searches
Resonant mass detectors

- Cryogenic bars with end transducers
- Use of SQUID low-noise amplifiers
- Vibration isolation
- Since 1997, Nearly-continuous coverage in coincident data runs

IGEC: International Gravitational Event Collaboration

Explorer @CERN

Allegro @LSU
Strain Noise Amplitude of IGEC2 detectors

![Graph showing strain noise amplitude for IGEC2 detectors.](image)
Ground based interferometers

- TAMA Japan 300m
- Virgo Italy 3000m
- AIGO Australia future
- LIGO Washington 2000m & 4000m
- LIGO Louisiana 4000m
- GEO Germany 600m
Interferometric gravitational wave detection

- **Suspended Interferometers**
  - Suspended mirrors in “free-fall”
  - Michelson IFO is “natural” GW detector
  - Broad-band response (~50 Hz to few kHz)
  - Waveform information (e.g., chirp reconstruction)

LIGO design length sensitivity: $10^{-18}$m
What Limits Sensitivity of Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels
Interferometers in Asia, Australia

TAMA 300 (Japan) (300-m)

AIGO (Australia) (80-m, but 3-km site)

Longest running detector: 9 data runs!

Operated by ACIGA; part of LIGO Scientific Collaboration.
Interferometers in Asia, Australia

TAMA 300 (Japan)  
(300-m)

AIGO (Australia)  
(80-m, but 3-km site)

Displacement noise level of TAMA300  
(2003/11/04)

Corresponds to a best strain sensitivity of $2.0 \times 10^{-21} /\sqrt{\text{Hz}}$

Operated by ACIGA; part of LIGO Scientific Collaboration.
Virgo Optical Configuration

Virgo Optical Configuration

- Laser: Nd:YAG
  - \(\lambda = 1.064 \, \mu m\)
  - \(\mathcal{P}_0 = 20 \, W\)

- Input mode-cleaner (length=150m)

- Output mode-cleaner
  - Photodetection (InAsGa)

- Recycling mirror

- Beam splitter

- Fabry-Perot
  - Finesse=50

- Length: 3 km
“Long Suspensions”
• inverted pendulum
• five intermediate filters

Suspension vertical transfer function measured and simulated (prototype)
GEO600 Optical Configuration

12W laser
mode cleaner

power recycling mirror
interferometer with „dual recycling“
signal recycling mirror

mode cleaner

photo detector

Courtesy B. Willke
GEO600 Seismic Isolation and Suspension

rotational stage
stack stabiliser
flex-pivot
passive layer
active layer
spacer
cantilever spring
damping arm
upper mass
cantilever spring
intermediate mass
10 cm
reaction mass
test mass
3 mm
2 stacks have been omitted for clarity

1.0 m
LIGO – Laser Interferometer Gravitational Wave Observatory

• Three interferometers at two distant sites
• Design philosophy: rely on proven technologies, scale up from prototype by two-orders of magnitude
• Achieved design sensitivity in Nov 05, currently operating with GEO in data-collection “science” mode

http://maps.google.com

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LIGO noise progress

Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs

$10^{-16}$ to $10^{-24}$

$LIGO$ $SRD$ $Goal,$ $4km$
Comparing strain noise

Sensitivity

- Virgo C7 (Sep 2005)
- Virgo WSR1 (8 Sep 2006)
- LHO 2km (18 Jun 2006)
- LHO 4km (13 Mar 2006)
- LLO 4km (04 Jun 2006)

GEO 600 (typical S5 2006)
Ground-based instruments

- **TAMA300**
  - TAMA300 Tokyo Japan
  - 1 300 m interferometer

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  - 1 300 m interferometer

- **ALLEGRO**
  - Baton Rouge LA
  - 1 Bar detector

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  - 1 Bar detector

- **Nautilus, Italy**
  - 1 Bar detector

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  - 1 Bar detector

- **Explorer, CERN**
  - 1 Bar detector

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  - 1 Bar detector

- **VIRGO**
  - VIRGO Pisa Italy
  - 1 3 km interferometer

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  - VIRGO Pisa Italy
  - 1 3 km interferometer

- **GEO600**
  - GEO600 Hannover Germany
  - 1 600 m interferometer

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  - GEO600 Hannover Germany
  - 1 600 m interferometer

- **LIGO Hanford**
  - LIGO Hanford WA
  - 1 4km, 1 2km interferometer

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  - LIGO Hanford WA
  - 1 4km, 1 2km interferometer

- **LIGO Livingston**
  - LIGO Livingston County LA
  - 1 4 km interferometer

- **LIGO Livingston**
  - LIGO Livingston County LA
  - 1 4 km interferometer
LISA is a joint ESA/NASA mission with launch date in the time frame 2014/15

- A gravitational wave telescope in the frequency band $10^{-5}$ - 1 Hz
- All sky monitor
- 3 drag-free satellites separated by $5 \times 10^6$ km, and trailing the earth by 20 deg
- Precision 10 pm
- Redundancy if one spacecraft fails
- Beam pattern from roll
Concluding remarks

- Search for direct detection of gravitational waves complicated by tiny signal, $\delta L \sim 10^{-18}\text{m}$; space is stiff, and sources are distant
- Requires cooperation in a global network of detectors
- Expect to make first detection within the next decade, possibly with existing detectors
- But for the next two days…
Estimated noise limits for S2 (as planned in October 2002)

(expected from targeted improvements)
Science runs and analyses

LIGO Hanford control room
31 Mar 2006 – S5
What would a pulsar look like?

- Post-processing step: find points on the sky and in frequency that exceeded threshold in many of the sixty ten-hour segments.
- Software-injected fake pulsar signal is recovered below.

Simulated (software) pulsar signal in S3 data

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Advanced LIGO

Detector Improvements:

New suspensions:

Single $\rightarrow$ Quadruple pendulum

Lower suspensions thermal noise in bandwidth

Improved seismic isolation:

Passive $\rightarrow$ Active

Lowers seismic “wall” to $\sim 10$ Hz