LIGO and the Search for Gravitational Waves

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Sir Isaac Newton

Universal Gravitation

- Three laws of motion and law of gravitation (centripetal force) disparate phenomena
  - eccentric orbits of comets
  - cause of tides and their variations
  - the precession of the earth’s axis
  - the perturbation of the motion of the moon by gravity of the sun

- Solved most known problems of astronomy and terrestrial physics
  - Work of Galileo, Copernicus and Kepler unified.
Einstein’s Theory of Gravitation

Newton’s Theory

“instantaneous action at a distance”

Einstein’s Theory

information carried by gravitational radiation at the speed of light
Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object.

- Imagine space as a stretched rubber sheet.
- A mass on the surface will cause a deformation.
- Another mass dropped onto the sheet will roll toward that mass.
Mercury’s elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.

Astronomers had been aware for two centuries of a small flaw in the orbit, as predicted by Newton's laws.

Einstein's predictions exactly matched the observation.
New Wrinkle on Equivalence

**bending of light**

- Not only the path of matter, but even the path of light is affected by gravity from massive objects

- First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

- Their measurements showed that the light from these stars was bent as it grazed the Sun, by the exact amount of Einstein's predictions.

> The light never changes course, but merely follows the curvature of space. Astronomers now refer to this displacement of light as gravitational lensing.
Einstein’s Theory of Gravitation

**experimental tests**

“Einstein Cross”
The bending of light rays

**gravitational lensing**

Quasar image appears around the central glow formed by nearby galaxy. The Einstein Cross is only visible in southern hemisphere.

In modern astronomy, such gravitational lensing images are used to detect a ‘dark matter’ body as the central object.
Einstein’s Theory of Gravitation

gravitational waves

• Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the transverse traceless gauge the formulation becomes a familiar wave equation

$$(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}) h_{\mu\nu} = 0$$

• The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).

• Since gravity is spin 2, the waves have two components, but rotated by 45° instead of 90° from each other.

$$h_{\mu\nu} = h_+ (t - z / c) + h_\times (t - z / c)$$
Einstein’s Theory of Gravitation

gravitational waves

- a necessary consequence of Special Relativity with its finite speed for information transfer

- time dependent gravitational fields come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light

gravitational radiation
binary inspiral of compact objects
Gravitational Waves

*the evidence*

**Neutron Binary System**

PSR 1913 + 16 -- Timing of pulsars

- Separated by $10^6$ miles
- $m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$

**Prediction from general relativity**

- Spiral in by 3 mm/orbit
- Rate of change orbital period

$\sim 8$ hr
Hulse and Taylor

emission of gravitational waves

- due to loss of orbital energy
- period speeds up 25 sec from 1975-98
- measured to ~50 msec accuracy
- deviation grows quadratically with time
Direct Detection

Laboratory Experiment

*a la Hertz*

Experimental Generation and Detection of Gravitational Waves

*gedanken experiment*

\[ f_{\text{rot}} = 1 \text{ kHz} \]
\[ h_{\text{lab}} = 2.6 \times 10^{-33} \text{ m x } 1/\text{R} \]
\[ R = \text{detector distance (}> 1 \text{ wavelength)} = 300 \text{ km} \]
\[ h_{\text{lab}} = 9 \times 10^{-39} \]

This is too weak by about 16 orders of magnitude!
Astrophysical Signatures

**data analysis**

- **Compact binary inspiral**: "chirps"
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates

- **Supernovae / GRBs**: "bursts"
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors

- **Pulsars in our galaxy**: "periodic"
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes

- **Cosmological Signals**: "stochastic background"
Radiation of Gravitational Waves from binary inspiral system

Waves propagates at the speed of light
Two polarizations at 45 deg (spin 2)

LISA
The Laser Interferometer Space Antenna (LISA)

- The center of the triangle formation will be in the ecliptic plane
- 1 AU from the Sun and 20 degrees behind the Earth.
- EM waves are studied over ~20 orders of magnitude
  » (ULF radio → HE γ-rays)

- Gravitational Waves over ~10 orders of magnitude
  » (terrestrial + space)
Suspended mass Michelson-type interferometers on earth’s surface detect distant astrophysical sources

International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.
Michelson Interferometer

- **Suspended Masses**
- **End Mirror**
- **Beam Splitter**
- **Laser**
- **Screen**

**Change in arm length is 10^{-18} meters**
Recycling Mirror

Optical Cavity

Beam Splitter

Laser

Photodetector

4 km or 2-1/2 miles

Suspended Test Masses
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
Noise Floor

40 m prototype

- Displacement sensitivity in 40 m prototype.
- Comparison to predicted contributions from various noise sources.

Sensitivity demonstration
Phase Noise

splitting the fringe

expected signal → $10^{-10}$ radians phase shift

demonstration experiment

- spectral sensitivity of MIT phase noise interferometer
- above 500 Hz shot noise limited near LIGO I goal
- additional features are from 60 Hz powerline harmonics, wire resonances (600 Hz), mount resonances, etc
Signals in Coincidence

Hanford Observatory

Livingston Observatory

3002 km (Ltc = 10 ms)
Detection Strategy

**coincidences**

- **Two Sites - Three Interferometers**
  - Single Interferometer: non-gaussian level ~50/hr
  - Hanford (Doubles): correlated rate (x1000) ~1/day
  - Hanford + Livingston: uncorrelated (x5000) <0.1/yr

- **Data Recording (time series)**
  - gravitational wave signal (0.2 MB/sec)
  - total data (16 MB/s)
  - on-line filters, diagnostics, data compression
  - off line data analysis, archive etc

- **Signal Extraction**
  - signal from noise (vetoes, noise analysis)
  - templates, wavelets, etc
LIGO
Livingston Observatory
LIGO
Hanford Observatory
<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Construction Underway (mostly civil)</td>
</tr>
<tr>
<td>1997</td>
<td>Facility Construction (vacuum system)</td>
</tr>
<tr>
<td>1998</td>
<td>Interferometer Construction (complete facilities)</td>
</tr>
<tr>
<td>1999</td>
<td>Construction Complete (interferometers in vacuum)</td>
</tr>
<tr>
<td>2000</td>
<td>Detector Installation (commissioning subsystems)</td>
</tr>
<tr>
<td>2001</td>
<td>Commission Interferometers (first coincidences)</td>
</tr>
<tr>
<td>2002</td>
<td>Sensitivity studies (initiate short data taking runs)</td>
</tr>
<tr>
<td>2003+</td>
<td>LIGO I data run (one year integrated data at h ~ 10^{-21})</td>
</tr>
<tr>
<td>2006</td>
<td>Begin LIGO II installation</td>
</tr>
</tbody>
</table>
LIGO Facilities

beam tube enclosure

- minimal enclosure
- reinforced concrete
- no services

Figure 2.1-1 -- Cross Section of Design Baseline at Hanford
LIGO beam tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!
Interferometry is limited by three fundamental noise sources:
- **seismic noise** at the lowest frequencies
- **thermal noise** at intermediate frequencies
- **shot noise** at high frequencies

Many other noise sources lurk underneath and must be controlled as the instrument is improved.
Beam Tube *bakeout*

- $I = 2000$ amps for ~ 1 week
- no leaks !
- final vacuum at level where not limiting noise, even for future detectors

26-March-02
LIGO
vacuum equipment
Vacuum Chambers

*vibration isolation systems*

- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Compensate for microseism at 0.15 Hz by a factor of ten
- Compensate (partially) for Earth tides
Seismic Isolation

springs and masses

damped spring
cross section
Seismic Isolation

**suspension system**

- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz

suspension assembly for a core optic
Thermal Noise $\sim k_B T/\text{mode}$

Strategy: Compress energy into narrow resonance outside band of interest → require high mechanical Q, low friction
LIGO Noise Curves
modeled sensitivity

wire resonances
Core Optics

*fused silica*

- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q’s > 2 x 10^6

Caltech data

CSIRO data
Core Optics
installation and alignment
ITMx Internal Mode Ringdowns

9.675 kHz; Q ~ 6e+5

14.3737 kHz; Q = 1.2e+7
LIGO Laser

- Nd:YAG
- 1.064 µm
- Output power > 8W in TEM00 mode
Commissioning

configurations

- Mode cleaner and Pre-Stabilized Laser
- 2km one-arm cavity
- Short Michelson interferometer studies
- Lock entire Michelson Fabry-Perot interferometer

“First Lock”
Why is Locking Difficult?

One meter, about 40 inches

\[ \div 10,000 \quad \frac{\text{One meter, about 40 inches}}{10,000} = \text{Earthtides, about 100 microns} \]

\[ \div 100 \quad \frac{\text{Earthtides, about 100 microns}}{100} = \text{Microseismic motion, about 1 micron} \]

\[ \div 10,000 \quad \frac{\text{Microseismic motion, about 1 micron}}{10,000} = \text{Precision required to lock, about } 10^{-10} \text{ meter} \]

\[ \div 100,000 \quad \frac{\text{Precision required to lock, about } 10^{-10} \text{ meter}}{100,000} = \text{Nuclear diameter, } 10^{-15} \text{ meter} \]

\[ \div 1,000 \quad \frac{\text{Nuclear diameter, } 10^{-15} \text{ meter}}{1,000} = \text{LIGO sensitivity, } 10^{-18} \text{ meter} \]
Laser stabilization

- Deliver pre-stabilized laser light to the 15-m mode cleaner
  - Frequency fluctuations
  - In-band power fluctuations
  - Power fluctuations at 25 MHz

- Provide actuator inputs for further stabilization
  - Wideband
  - Tidal

**Diagram:**
- PSL: 10-Watt Laser
  - 10^{-1} Hz/Hz^{1/2}

- IO: 15m
  - 10^{-4} Hz/Hz^{1/2}

- Interferometer: 4 km
  - 10^{-7} Hz/Hz^{1/2}
Prestabilized Laser performance

- > 18,000 hours continuous operation
- Frequency and lock very robust
- $\text{TEM}_{00}$ power > 8 watts
- Non-$\text{TEM}_{00}$ power < 10%
**LIGO**

“first lock”

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**Diagram Description:**
- **Laser**
- **X Arm**
- **Y Arm**
- **Composite Video**

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**Legend:**
- Red line: Laser path
- Purple shapes: Reflectors
- Blue boxes: Detectors

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**Note:**
- The diagram illustrates the "first lock" configuration of the Laser Interferometer Gravitational-Wave Observatory (LIGO) setup.
Watching the Interferometer Lock

Laser

Y Arm

X Arm

Y arm

X arm

Reflected light

Anti-symmetric port

Signal

2 min
Lock Acquisition
Engineering Test Run

2 weeks – Jan 02

PRELIMINARY

4 Km Hanford

4 Km Livingston

2 Km Hanford
Strain Spectra for E7
comparison with design sensitivity
LIGO Improvements LHO 2K – Jan 02

- Closed feedback loop from arms to laser frequency
- Reallocation of gains within length control servo system
An earthquake occurred, starting at UTC 17:38.

The plot shows the band limited rms output in counts over the 0.1-0.3Hz band for four seismometer channels. We turned off lock acquisition and are waiting for the ground motion to calm down.

From electronic logbook 2-Jan-02
Seismo-Watch
Earthquake Alert Bulletin No. 02-64441

Preliminary data indicates a significant earthquake has occurred:
Regional Location: VANUATU ISLANDS
Magnitude: 7.3M

Greenwich Mean Date: 2002/01/02
Greenwich Mean Time: 17:22:50
Latitude: 17.78S
Longitude: 167.83E
Focal depth: 33.0km
Analysis Quality: A

Source: National Earthquake Information Center (USGS-NEIC)
Seismo-Watch, Your Source for Earthquake News and Information.
Visit http://www.seismo-watch.com

All data are preliminary and subject to change.
Analysis Quality: A (good), B (fair), C (poor), D (bad)
Magnitude: Ml (local or Richter magnitude), Lg (mblg), Md (duration),
Detecting the Earth Tides

Sun and Moon
Astrophysical Signatures

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- **Cosmological Signals**
  - "stochastic background"
“Chirp Signal”

binary inspiral

determine

• distance from the earth \( r \)
• masses of the two bodies
• orbital eccentricity \( e \) and orbital inclination \( i \)
Interferometer Data

40 m prototype

Real interferometer data is UGLY!!!
(Gliches - known and unknown)
The Problem

How much does real data degrade complicate the data analysis and degrade the sensitivity??

Test with real data by setting an upper limit on galactic neutron star inspiral rate using 40 m data
“Clean up” data stream

Effect of removing sinusoidal artifacts using multi-taper methods

Non stationary noise
Non gaussian tails
Inspiral ‘Chirp’ Signal

Template Waveforms

“matched filtering”
687 filters

44.8 hrs of data
39.9 hrs arms locked
25.0 hrs good data

sensitivity to our galaxy
$h \sim 3.5 \times 10^{-19} \text{ mHz}^{-1/2}$
effective rate $\sim 10^{-6}/\text{yr}$

26-March-02
Optimal Signal Detection

Want to “lock-on” to one of a set of known signals

Requires:
- source modeling
- efficient algorithm
- many computers
Detection Efficiency

- Simulated inspiral events provide end to end test of analysis and simulation code for reconstruction efficiency
- Errors in distance measurements from presence of noise are consistent with SNR fluctuations
Results from 40m Prototype

Loudest event used to set upper-limit on rate in our Galaxy:

\[ R_{90\%} < 0.5 \text{ / hour} \]
Setting a limit

Upper limit on event rate can be determined from SNR of 'loudest' event

Limit on rate:
\[ R < 0.5/\text{hour with } 90\% \text{ CL} \]
\[ \varepsilon = 0.33 = \text{detection efficiency} \]

An ideal detector would set a limit:
\[ R < 0.16/\text{hour} \]
LIGO

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“Burst Signal”

supernova

- Pre-supernova star
- Collapse of the core
- Interaction of shock with collapsing envelope
- Explosive ejection of envelope
- Neutrinos emitted
- Light emitted
- Light brightens by $\approx 10^8$ times

gravitational waves

nu's
Supernovae

gravitational waves

Non axisymmetric collapse

Rate
1/50 yr - our galaxy
3/yr - Virgo cluster

‘burst’ signal

Rate
1/50 yr - our galaxy
3/yr - Virgo cluster
Supernovae
asymmetric collapse?

pulsar proper motions

Velocities -
  ▪ young SNR(pulsars?)
  ▪ > 500 km/sec

Burrows et al

▪ recoil velocity of matter and neutrinos
Supernovae signatures and sensitivity

![Graph of gravity wave power spectra and sensitivity of LIGO to burst sources.](image)
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Periodic Signals

*spinning neutron stars*

- Isolated neutron stars with deformed crust
- Newborn neutron stars with r-modes
- X-ray binaries may be limited by gravitational waves
“Periodic Signals”

pulsars sensitivity

- **Pulsars in our galaxy**
  - non axisymmetric: 
    \[ 10^{-4} < \varepsilon < 10^{-6} \]
  - science: neutron star precession; interiors
    - narrow band searches best
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“Stochastic Background”

**cosmological signals**

‘Murmurs’ from the Big Bang

**signals from the early universe**

Cosmic microwave background
- **Detection**
  - Cross correlate Hanford and Livingston Interferometers
- **Good Sensitivity**
  - GW wavelength $\geq 2x$ detector baseline $\Rightarrow f \leq 40$ Hz
- **Initial LIGO Sensitivity**
  - $\Omega \geq 10^{-5}$
- **Advanced LIGO Sensitivity**
  - $\Omega \geq 5 \times 10^{-9}$
Stochastic Background

coherece plots LHO 2K & LHO 4K
Stochastic Background

coherece plot LHO 2K & LLO 4K
Analytic calculation of expected upper limits (~50 hrs):

\[ \Omega \approx 2 \times 10^5 \text{ for } \text{LLO-LHO 2k, } \Omega \approx 6 \times 10^4 \text{ for LHO 2k-LHO 4k} \]

Coherence measurements of GW channels show little coherence for LLO-LHO 2k correlations

Power line monitor coherence investigations suggest coherence should average out over course of the run

Plan to investigate effect of line removal on LHO 2k-LHO 4k correlations (e.g., reduction in correlated noise, etc.)

Plan to inject simulated stochastic signals into the data and extract from the noise

Plan to also correlate LLO with ALLEGRO bar detector

ALLEGRO was rotated into 3 different positions during E7
Stochastic Background

projected sensitivities
Run Plan
commissioning & data taking

- **Science 1 run: 13 TB data**  
  "Upper Limits"
  - 29 June - 15 July
  - 2.5 weeks - comparable to E7
  - Target sensitivity: 200x design

- **Science 2 run: 44 TB data**  
  "Upper Limits"
  - 22 November - 6 January 2003
  - 8 weeks -- 15% of 1 yr
  - Target sensitivity: 20x design

- **Science 3 run: 142 TB data**  
  "Search Run"
  - 1 July 2003 -- 1 January 2004
  - 26 weeks -- 50% of 1 yr
  - Target sensitivity: 5x design
LIGO

conclusions

- LIGO construction complete
- LIGO commissioning and testing ‘on track’
- Engineering test runs underway, during period when emphasis is on commissioning, detector sensitivity and reliability. (Short upper limit data runs interleaved)
- First Science Search Run: first search run will begin during 2003
- Significant improvements in sensitivity anticipated to begin about 2006