Klopsteg Memorial Lecture

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“Catching the Waves with LIGO”
Sir Isaac Newton

- Perhaps the most important scientist of all time!
- Invented the scientific method in *Principia*
- Greatest scientific achievement: *universal gravitation*
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.
Albert Einstein

- The Special Theory of Relativity (1905) overthrew commonsense assumptions about space and time. Relative to an observer, near the speed of light, both are altered
  » distances appear to stretch
  » clocks tick more slowly
Newton’s Theory

“instantaneous action at a distance”

Einstein’s Theory

information carried by gravitational radiation at the speed of light
Einstein’s spacetime wrinkles

- Discards concept of absolute motion; instead treats only relative motion between systems
- Space and time no longer viewed as separate; rather as four dimensional space-time
- Gravity described as a warpage of space-time, not a force acting at a distance
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.
Einstein’s Theory of Gravitation

**experimental tests**

Mercury’s orbit

*perihelion shifts forward*

*an extra +43”/century*

*compared to Newton’s theory*

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

• 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 – Hulse & Taylor
PSR 1913 + 16 -- Timing of pulsars

**Neutron Binary System**
- 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

**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.

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 $45^0$ instead of $90^0$ from each other.

\[ h_{\mu\nu} = h_+ (t - \frac{z}{c}) + h_\times (t - \frac{z}{c}) \]
Direct Detection

*Laboratory experiment*

**a la Hertz**

"*Gedanken experiment*" a la Hertz

**Experimental Generation and Detection of Gravitational Waves**

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

*This is too weak by about 16 orders of magnitude!*

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Direct Detection

astrophysical sources

Detectors in space

LISA

Gravitational Wave
Astrophysical Source

Terrestrial detectors

LIGO, TAMA, Virgo, AIGO
Astrophysical Sources

**signatures**

- 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 background "stochastic"
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.
International network (LIGO, Virgo, GEO, TAMA, AIGO) of suspended mass Michelson-type interferometers on earth’s surface detect distant astrophysical sources.

Free masses

Suspended test masses
Astrophysics Sources

*frequency range*

- 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 Interferometer

**the concept**

- An interferometric gravitational wave detector
  - A laser is used to measure the relative lengths of two orthogonal cavities (or arms)
- Arms in LIGO are 4km
  - Current technology then allows one to measure $h = \delta L/L \sim 10^{-21}$ which turns out to be an interesting target

...causing the interference pattern to change at the photodiode

As a wave passes, the arm lengths change in different ways....
How Small is $10^{-18}$ Meter?

- One meter, about 40 inches
- Human hair, about 100 microns
- Wavelength of light, about 1 micron
- Atomic diameter, $10^{-10}$ meter
- Nuclear diameter, $10^{-15}$ meter
- LIGO sensitivity, $10^{-18}$ meter
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

sensitivity demonstration

- displacement sensitivity in 40 m prototype.
- comparison to predicted contributions from various noise sources
Phase Noise

splitting the fringe

epected 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
LIGO Sites

Hanford Observatory

Livingston Observatory

3002 km (Ltc = 10 ms)
LIGO
Livingston Observatory
LIGO

Hanford Observatory
Interferometer

locking

Requires test masses to be held in position to $10^{-10}$--$10^{-13}$ meter:
“Locking the interferometer”

Light bounces back and forth along arms about 150 times

Light is “recycled” about 50 times
Lock Acquisition
LIGO
watching the interferometer lock

[Diagram of LIGO setup showing Laser, X Arm, Y Arm, and Composite Video]
LIGO

watching the interferometer lock

2 min

Laser

Y Arm

X Arm

Reflected light

Anti-symmetric port

signal
LIGO Sensitivity History

Hanford 2K 06-02

Livingston 4K 06-02
Astrophysical Sources

**search efforts**

- **Compact binary inspiral:** "chirps"
  - NS-NS waveforms are well described
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- **Supernovae / GRBs:** "bursts"
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- **Pulsars in our galaxy:** "periodic"
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- **Cosmological Signals background** "stochastic"
“Stochastic Background”

*Cosmological signals*

‘Murmurs’ from the Big Bang

*Signals from the early universe*

Cosmic microwave background
Stochastic Background sensitivity

- **Detection**
  - Cross correlate Hanford and Livingston Interferometers

- **Good Sensitivity**
  - GW wavelength ≥ 2x detector baseline ⇒ $f \leq 40$ Hz

- **Initial LIGO Sensitivity**
  - $\Omega \geq 10^{-5}$

- **Advanced LIGO Sensitivity**
  - $\Omega \geq 5 \times 10^{-9}$
Stochastic Background

coherence plots LHO 2K & LHO 4K
Stochastic Background

coherence plot LHO 2K & LLO 4K

Coherence L1: LSC-AS-Q H2: LSC-AS-Q
GPS time = 693960022-693961245

Coherence L1: LSC-AS-Q H2: LSC-AS-Q
GPS time = 693960022-693961245
Stochastic Background

projected sensitivities
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
- Detection likely within the next decade!