Catching the Waves with LIGO

Barry Barish

Los Alamos National Laboratory
27-March-03
Gravitational Waves

"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)
General Relativity

the essential idea

\[ G_{\mu \nu} = 8\pi T_{\mu \nu} \]

- Gravity is not a force, but a property of space &
- Objects follow the shortest path through this warped spacetime; path is the same for all objects
  » Perception of space or time is relative
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.
A small crack in Newton’s theory ..... 

**perihelion shifts forward an extra +43”/century compared to Newton’s theory**
A new prediction …

*bending of light*

A massive object shifts apparent position of a star

Observation made 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.
Einstein’s 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.
A Conceptual Problem is solved!

Newton’s Theory
“instantaneous action at a distance”

Einstein’s Theory
information carried by gravitational radiation at the speed of light
Einstein’s Theory of Gravitation

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

- gravitational waves 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
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.

\[
h_{\mu\nu} = h_+(t - z/c) + h_\times(t - z/c)
\]
Detecting Gravitational Waves

Laboratory Experiment

a la Hertz

Experimental Generation and Detection of Gravitational Waves

gedanken experiment

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

This is too weak by about 16 orders of magnitude!
The evidence for gravitational waves

**Hulse & Taylor**

Neutron binary system

- separation = $10^6$ miles
- $m_1 = 1.4m_\odot$
- $m_2 = 1.36m_\odot$
- $e = 0.617$

**Prediction from general relativity**

- spiral in by 3 mm/orbit
- rate of change orbital period

PSR 1913 + 16

Timing of pulsars

$17 \text{ / sec}$

period $\sim 8 \text{ hr}$
“Indirect” detection 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.

Direct Detection

Gravitational Wave Astrophysical Source

Terrestrial detectors
LIGO, TAMA, Virgo, AIGO

Detectors in space
LISA
Detection in space

- Center of the triangle formation is in the ecliptic plane
- 1 AU from the Sun and 20 degrees behind the Earth.
Detection on Earth

simultaneously detect signal

decompose the polarization of gravitational waves
Frequency range of astrophysics sources

- Gravitational Waves over ~8 orders of magnitude
  - Terrestrial detectors and space detectors
Frequency range of astronomy

- EM waves studied over ~16 orders of magnitude
  - Ultra Low Frequency radio waves to high energy gamma rays
A New Window on the Universe

Gravitational Waves will provide a new way to view the dynamics of the Universe
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** "stochastic background"
The effect …

Leonardo da Vinci’s Vitruvian man

Stretch and squash in perpendicular directions at the frequency of the gravitational waves
Detecting a passing wave ....

A ring of free masses
Detecting a passing wave …. An Interferometer
I have greatly exaggerated the effect!!

If the Vitruvian man was 4.5 light years high, he would grow by only a ‘hairs width’
Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms
- Arms in LIGO are 4km
- Measure difference in length to one part in $10^{21}$ or $10^{-18}$ meters

...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 ~ 40 inches
- Human hair ~ 100 microns
- Wavelength of light ~ 1 micron
- Atomic diameter $10^{-10}$ m
- Nuclear diameter $10^{-15}$ m
- LIGO sensitivity $10^{-18}$ m
LIGO Organization

LIGO Laboratory
MIT + Caltech
~140 people
Director: Barry Barish

LIGO Science Collaboration
44 member institutions
> 400 scientists
Spokesperson: Rai Weiss

National Science Foundation

DESIGN
CONSTRUCTION
OPERATION

SCIENCE

Detector
R&D

UK
Germany
Japan
Russia
India
Spain
Australia

$
The Laboratory Sites

Laser Interferometer Gravitational-wave Observatory (LIGO)

Hanford Observatory

Livingston Observatory

3002 km
(c/2 = 10 ms)
LIGO
Livingston Observatory
LIGO
Hanford Observatory
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 steel
50 km of weld

NO LEAKS !!
LIGO vacuum equipment
LIGO Optic

Substrates: SiO$_2$
- 25 cm Diameter, 10 cm thick
- Homogeneity $< 5 \times 10^{-7}$
- Internal mode Q’s $> 2 \times 10^6$

Polishing
- Surface uniformity $< 1$ nm rms
- Radii of curvature matched $< 3$

Coating
- Scatter $< 50$ ppm
- Absorption $< 2$ ppm
- Uniformity $< 10^{-3}$
Core Optics
installation and alignment
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)
- IO (15m)
- Interferometer (4 km)
- Tidal
- Wideband

Frequencies:
- $10^{-1}$ Hz/Hz$^{1/2}$ for PSL
- $10^{-4}$ Hz/Hz$^{1/2}$ for IO
- $10^{-7}$ Hz/Hz$^{1/2}$ for Interferometer
Prestabralized Laser

performance

- > 20,000 hours continuous operation
- Frequency and lock very robust
- TEM\textsubscript{00} power > 8 watts
- Non-TEM\textsubscript{00} power < 10%
- Simplification of beam path outside vacuum reduces peaks
- Broadband spectrum better than specification from 40-200 Hz
LIGO
“first lock”

Composite Video

Y Arm

X Arm

signal

Laser
Watching the Interferometer Lock

Y Arm

Laser

X Arm

Y Arm

X Arm

Reflected light

Anti-symmetric port

signal

2 min

27-March-03

Los Alamos National Laboratory -- Colloquium
Lock Acquisition

- State 2
- State 3
- State 4

- Power Buildup
- Signals (arb. units)

- Sideband in PRC
- Carrier in Arm 1
- Carrier in Arm 2

- \( L_4 \) control
- \( L_4 \) control
- Determinant

Time
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
LIGO Sensitivity
Livingston 4km Interferometer

May 01
Jan 03
An earthquake occurred, starting at UTC 17:38.

From electronic logbook 2-Jan-02
Detecting the Earth Tides

Sun and Moon
Compact binary collisions: “chirps”

- Neutron Star – Neutron Star
  - waveforms are well described
- Black Hole – Black Hole
  - need better waveforms
- Search: matched templates

Simulation and Visualization by Maximilian Ruffert & Hans-Thomas Janka
Stars Form!

Collapsing gas clouds heat up and ignite nuclear burning, fusing hydrogen, helium to heavier elements.

Stars Burn!

Star becomes "layered", like an onion, with heavy elements fusing yet heavier elements at center.

Iron is the heaviest element that will fuse this way.

Stars Collapse!

As the end of the fusion chain is reached, nuclear burning can no longer provide the pressure to hold the star up under gravity.

The material in the star continues to crush together.

Eventually, the atoms in the star "melt" into a sea of electrons and nuclei. This sea resists compression and might stop collapse → "dwarf" star.

In more massive stars, electrons and nuclei are crushed into pure nuclear matter → "neutron star". This stiffer form of matter may halt collapse.

No other form of matter exists to stop collapse in heavier stars → space and time warpage increase until an "event horizon" forms → "black hole".

"dwarf star"
“Burst Signal”

supernova

gravitational waves

Pre-supernova star

Collapse of the core

Interaction of shock with collapsing envelope

Explosive ejection of envelope

neutrinos emitted

light emitted

Expanding remnant emitting X-rays, visible light, and radio waves. The collapsed stellar remnant may be observable as a pulsar.

Star brightens by \( \sim 10^8 \) times

νννν’s

light
Supernovae

gravitational waves

Non axisymmetric collapse

‘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
Spinning Neutron Stars

“periodic”

An afterlife of stars

Maximum gravitational wave luminosity of known pulsars
Early Universe

“correlated noise”

‘Murmurs’ from the Big Bang

Gravitational Waves

Early Universe

Cosmic Microwave background

WMAP 2003

Planck Time
10^{-43} SECONDS
Singularity
creates
Space & Time
of our universe

1 SECOND

100,000 YEARS

10 billion YEARS

SASKATOON
3 YEAR DATA

COBE DMR
4 YEAR DATA

27-March-03

Los Alamos National Laboratory -- Colloquium
Stochastic Background

**no observed correlations**

- Strength specified by *ratio of energy density in GWs to total energy density* needed to close the universe:

\[
\Omega_{GW}(f) = \frac{1}{\rho_{\text{critical}}} \frac{d\rho_{GW}}{d(\ln f)}
\]

- Detect by *cross-correlating* output of two GW detectors:

  First LIGO Science Data (Lazzarini)

  **Preliminary limits from 7.5 hr of data**
Stochastic Background
sensitivities and theory

LIGO

results

projected

E7

S1

S2

LIGO

Adv LIGO

27-March-03 Los Alamos National Laboratory -- Colloquium 54
Advanced LIGO

2007 +

Enhanced Systems

- laser
- suspension
- seismic isolation
- test mass

Improvement factor in rate
\( \sim 10^4 \)

+ narrow band optical configuration
Advanced LIGO

improved subsystems

Multiple Suspensions

Active Seismic

Sapphire Optics

Higher Power Laser
Conclusions

- **LIGO commissioning is well underway**
  - Good progress toward design sensitivity

- **Science Running is beginning**
  - Initial results from our first LIGO data run

- **Our Plan**
  - Improved data run is underway
  - Our goal is to obtain one year of integrated data at design sensitivity before the end of 2006
  - Advanced interferometer with dramatically improved sensitivity – 2007+

- **LIGO should be detecting gravitational waves within the next decade!**
to
Catching
the
Waves ....