The Search for Gravitational Waves

Barry Barish
Caltech

Cal Poly Pomona
18-Oct-02
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.
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 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

Gravitational Waves

**the evidence**

**Neutron Binary System – Hulse & Taylor**

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

**Emission of gravitational waves**

![Graph comparing observations of the binary pulsar PSR1913+16 and the prediction of general relativity based on loss of orbital energy via gravitational waves.](chart.png)
• 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.

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

• 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.

$$h_{\mu\nu} = h_+ (t - z/c) + h_\times (t - z/c)$$
Direct Detection

*a laboratory experiment?*

*a la Hertz*

"gedanken experiment"*

Experimental Generation and Detection of Gravitational Waves*

![Laboratory Dumbbell System](image)

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

This is too weak by about 16 orders of magnitude!
Direct Detection

**astrophysical sources**

- **Gravitational Wave Astrophysical Source**
- **Terrestrial detectors**
  - LIGO, TAMA, Virgo, AIGO

**Detectors in space**
- LISA
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.
Gravitational Waves

*the effect*

Leonardo da Vinci’s Vitruvian man

stretch and squash in perpendicular directions at the frequency of the gravitational waves

The effect is greatly exaggerated!!

If the man was 4.5 light years high, he would grow by only a ‘hairs width’ LIGO (4 km), stretch (squash) = $10^{-18}$ m will be detected at frequencies of 10 Hz to $10^4$ Hz. It can detect waves from a distance of 600 $10^6$ light years
International network (LIGO, Virgo, GEO, TAMA, AIGO) of suspended mass Michelson-type interferometers on earth’s surface detect distant astrophysical sources.
- EM waves are studied over ~20 orders of magnitude
  » (ULF radio \(\rightarrow\) HE \(\gamma\)-rays)

- Gravitational Waves over ~10 orders of magnitude
  » (terrestrial + space)
Interferometers

international network

Simultaneously detect signal (within msec)

- LIGO
- GEO
- Virgo
- TAMA
- AIGO

Detection confidence
Locate the sources
Decompose the polarization of gravitational waves
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

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

- displacement sensitivity in 40 m prototype.
- comparison to predicted contributions from various noise sources
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
The Laboratory Sites

Laser Interferometer Gravitational-wave Observatory (LIGO)

Hanford Observatory

Livingston Observatory

3002 km
(L/c = 10 ms)
LIGO vacuum equipment
Core Optics

fused silica

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

LIGO measurements
- central 80 mm of 4ITM06 (Hanford 4K)
- rms = 0.16 nm
- optic far exceeds specification.

Surface figure = λ/ 6000
Core Optics
installation and alignment
Interferometer

"Locking the interferometer"

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

Signal

End test mass

Input test mass

Laser
Lock Acquisition
LIGO

watching the interferometer lock

Composite Video

Y Arm

Laser

X Arm

signal
LIGO

watching the interferometer lock

Laser

Y Arm

X Arm

signal

Y arm

X arm

Reflected light

Anti-symmetric port

2 min
Strain Sensitivities for the LIGO Livingston 4km Interferometer, E7 to S1

18 May 2001 - 13 August 2002  LIGO-G020451-00-E
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.
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
LIGO Goals and Priorities

- **Interferometer performance**
  - Integrate commissioning and data taking consistent with obtaining one year of integrated data at $h = 10^{-21}$ by end of 2006

- **Physics results from LIGO I**
  - Initial upper limit results by early 2003
  - First search results in 2004
  - Reach LIGO I goals by 2007

- **Advanced LIGO**
  - Prepare advanced LIGO proposal this fall
  - International collaboration and broad LSC participation
  - Advanced LIGO installation beginning by 2007
S1 run: science segments from 714150013 to 715614971

- L1 = 297hrs
- H1 = 235hrs
- H2 = 297hrs
- L1,H1 = 116hrs
- L1,H2 = 131hrs
- H1,H2 = 188hrs
- L1,H1,H2 = 95.7hrs

Preliminary
Astrophysical Sources
the search for gravitational waves

- 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”
“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)

LOCKING

NORMAL

RINGING

ROCKING
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

40 meter IFO output
10 Nov 1994 run 3

Histogram of Raw Data
ADC value (12 bit, signed)
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
$h \sim 3.5 \times 10^{-19}$ mHz$^{-1/2}$

expected rate $\sim 10^{-6}$/yr
Optimal Signal Detection

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

Requires:
- source modeling
- efficient algorithm
- many computers
- 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
Astrophysical Sources

the search for gravitational waves

- **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"
“Burst Signal”

supernova

- Pre-supernova star
- Collapse of the core
- Interaction of shock with collapsing envelope
- Neutrinos emitted
- Light emitted
- Explosive ejection of envelope
- Gravitational waves

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

Star brightens by $\approx 10^8$ times.
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
Astrophysical Sources
the search for gravitational waves

- **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”
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

Maximum gravitational wave luminosity of known pulsars
Pulsars in our galaxy

- non axisymmetric: $10^{-4} < \varepsilon < 10^{-6}$
- science: neutron star precession; interiors
- narrow band searches best
Astrophysical Sources
the search for gravitational waves

- 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”
“Stochastic Background”

*Cosmological signals*

‘Murmurs’ from the Big Bang

*Signals from the early universe*

Cosmic microwave background
Stochastic Background

coherence plot LHO 2K & LLO 4K
Stochastic Background

projected sensitivities
Advanced LIGO

Multiple Suspension

Active Seismic

Sapphire Optics

Higher Power Laser

Date: 10/25/2001
Time: 13:59:18
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 81.6271 nm
RMS: 13.2016 nm

X Center: 172.00
Y Center: 145.00
Radius: 163.00 pix
Terms: None
Filters: None
Masks:
Advanced LIGO

Enhanced Systems

- improved laser
- suspension
- seismic isolation
- test mass material
- narrow band optics

Improvement factor

$\sim 10^4$
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 begin in 2003

- Significant improvements in sensitivity anticipated to begin about 2006

- Detection is likely within the next decade!