Gravitational Waves and LIGO

Ray Frey, University of Oregon

1. GW Physics and Astrophysics
2. How to detect GWs – The experimental challenge
3. Prospects
Some predictions:

- Gravity influences both mass and energy
  - *e.g.* bending of light in regions with gravitational field
  - 1919 Eddington → Gravitational lensing
- Many small deviations from Newtonian gravity in “weak” fields
  - Gravitational “redshift” (*e.g.* clocks on satellites are faster)
  - Perihelion advance of mercury
  - Global Positioning System would not work without GR corrections
- “Strong” field effects
  - Black holes; \( R_s = \frac{2GM}{c^2} \)
- Spacetime structure of universe – evolution of spacetime from Big Bang
- And gravitational radiation (gravitational waves)
  - “Ripples in spacetime”
    - Propagation at c; two polarization states (+,x)
Evidence for Gravitational Waves

PSR 1913+16 Binary n-star system

- Pulsar period observed over 25 years
  - Taylor and Hulse

Cumulative shift of periastron time

• Goals:
  ▪ Establish GW detection – test General Relativity
  ▪ Use GW as an astrophysical tool
• Unexplored territory!
  ▪ GW revolution like radio astronomy?
GW Sources

- GW emission requires time varying quadrupole moment of mass distribution

- Strain estimate:

\[ h \sim \left( \frac{GM}{c^2} \right) \left( \frac{v^2}{c^2} \right) \frac{1}{r} \]

For \( 1M_\odot \Rightarrow R_s = 2GM_\odot/c^2 = 3 \text{ km} \)

If \( v \approx c \), then at \( r = 15 \text{ Mpc} \):

\[ h \sim 3 \times 10^{-21} \]
GW Interferometer Principle
Interferometer sensitivity

- **Strain due to space-time warpage:** \( h = \frac{\delta L}{L} \)
  
  » For \( h \approx 10^{-21} \) and \( L \approx 1 \text{ km} \), then \( \delta L \approx 10^{-18} \text{ m} \)

- **Change in light travel time (one bounce):** \( \delta t = 2 \frac{\delta L}{c} = 2hL/c \)

- **Gives change in phase:** \( \delta \Phi = 2\pi f \delta t = \frac{4\pi Lh}{\lambda} \)
  
  » \( L \approx 100 \times 1 \text{ km} \)
  
  » \( \lambda = 1 \mu \text{m} \)
  
  » Let \( h \approx 10^{-21} \)

\[ \Rightarrow \delta \Phi \approx 10^{-9} \text{ rad} \]

- \( \delta \Phi \approx 10^{-7} \) is commonplace

- **Need to improve by factor 100; and in a large system**
Interferometer parameters

- Long baseline $\sim 1$ km
- Cavity storage time $\sim 1$ ms ($\sim 100$ bounces)
- High laser power
  - Power recycling (x30)
  - Few watts in; few kW in arms
How small is $10^{-18}$ m?

- $\div 10,000$: Human hair, about 100 microns
- $\div 100$: Wavelength of light, about 1 micron
- $\div 10,000$: Atomic diameter, $10^{-10}$ meter
- $\div 100,000$: Nuclear diameter, $10^{-15}$ meter
- $\div 1,000$: LIGO sensitivity, $10^{-18}$ meter
Experimental features

- Extensive use of servo loops
- Null measurements
  - dark fringe kept centered on photodiode
- RF heterodyne measurement of $\delta \Phi$
- Power recycling
- Isolation and monitoring of environment
What Limits Sensitivity of Interferometers?

- Seismic noise & vibration limit at low frequencies
- Thermal noise of suspensions and test masses
- Quantum nature of light (Shot Noise) limits at high frequencies
- Limitations of facilities much lower (LIGO)
Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1, S2, S3

LIGO-G030548-02-E
Inspiral sensitivity

Compact binary mergers

LIGO sensitivity to coalescing binaries
Astrophysical signal types

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

- Supernovae / GRBs: "bursts"
  - "unmodelled" search
  - triggered search: coincidence with photon or neutrino detections

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

- Cosmological Signals "stochastic background"

June 16, 2004
R. Frey
QNet
Gamma Ray Bursts

GRB030329
Gamma-ray lightcurve from the HETE-2 spacecraft

Light curve (Fregate_B) that triggered H2652
Trigger_20030329_113714.70 = 1.31558670.8 = 732973047.70

Source: GSFC

June 16, 2004
R. Frey
An International Network of Interferometers

Simultaneously detect signal (within msec)

- **LIGO**
- **GEO**
- **Virgo**
- **TAMA**

- detection confidence
- locate the sources
- decompose the polarization of gravitational waves
Status of detectors

• **LIGO:** 2 sites, $L = 4\text{km}$
  - Science running interleaved with planned improvements
  - S1 analyses and papers completed (upper limits)
  - S2 and S3 analyses being completed

• **VIRGO:** $L = 3\text{km}$
  - Commissioning full interferometer
  - Advanced suspensions

• **GEO:** $L = 0.6\text{km}$
  - Run with LIGO S1, S3, … (improvements interleaved)
  - Advanced suspensions

• **TAMA:** $L = 0.3\text{km}$
  - Run with LIGO S2, S3, …

• **AIGO:** R&D facility
Laser Interferometer Gravitational-wave Observatory (LIGO)

Hanford Observatory

Livingston Observatory

3002 km (Ljc = 10 ms)
Vacuum equipment – corner station
Optic

Substrates: SiO$_2$
25 cm Diameter, 10 cm thick
Homogeneity < 5 x 10$^{-7}$
Internal mode Q’s > 2 x 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 Suspension and Control

Shadow sensors & coil actuators provide damping and control forces.

Mirror is balanced on 30 micron diameter wire to 1/100th degree of arc.
Science Running

Hanford control room
Active Seismic Isolation

Hydraulic External Pre-Isolator (HEPI)

- Offload Springs
- Crossbeam
- Hydraulic Actuator (Horizontal)
- Hydraulic Lines & Valves
- Pier
- BSC
- HAM

R. Frey  QNet  23
The need for improved sensitivity

• Probe the Virgo cluster and beyond

• Sample cosmologically located sources (eg GRBs) with good statistics

• Advanced LIGO will increase observed space by $10^4$
Advanced LIGO
improved subsystems

Multiple Suspensions
Active Seismic

Sapphire Optics

Higher Power Laser

Date: 10/25/2001
X Center: 172.00

Time: 13:59:18
Y Center: 145.00

Wavelength: 1.064 um
Radius: 163.00 pix

Pupil: 100.0 %
Terms: None

PV: 81.6271 nm
Filters: None

RMS: 13.2016 nm
Masks:
LISA: Interferometers in space

- Can probe low-frequency sources
Prospects

• First GW discoveries ??

• Advanced LIGO
  - Plan: Start shutdown for installation ~2007

• Maturation of the field of GW astronomy ??

• LISA
Summary

• Goals:
  ▪ Establish gravitational wave detection – test General Relativity
  ▪ Use GW as an astrophysical tool
• New generation of ground-based GW interferometric detectors turning on well
  ▪ approaching design sensitivity
  ▪ Impressive technological achievement
• Science Running has started
  ▪ GW physics and astrophysics
  ▪ Capable now of seeing sources outside our local group of galaxies
• Major upgrades planned