The Current State of Gravitational Wave Detection

R. Weiss, MIT
ADM-50 Texas A&M
November 8, 2009
1. History of Sub-Panel

This report is a summary of the deliberations and the recommendations of a Sub-Panel of the Management and Operations Working Group in Shuttle Astronomy commissioned by Dr. Nancy G. Roman of NASA Headquarters to consider the role of the space program in the field of experimental relativity and gravitation. The panel members are Professors Peter Bender of the University of Colorado and the National Bureau of Standards, Charles Misner of the University of Maryland, Robert V. Pound of Harvard University and Rainer Weiss of M.I.T., chairman. The panel met 4 times during 1975, and at several of the meetings it was joined by visitors interested in the field. The visitors were Dr. Rudolf Decher of NASA Huntsville, Dr. Nancy Roman, NASA Headquarters, Professors James Peebles of Princeton University, Irwin Shapiro of M.I.T. and Kip Thorne of Cal Tech.

The report introduces the reader to the fundamental problems in experimental relativity and gravitation and then follows with sections on various areas in the field. Each section reviews the present status of research and brings forward suggestions where the space program may have an impact.

2. Introduction

Gravitation is at the same time the dominant force in the universe for matter in the large as well as the weakest known fundamental interaction in nature. Gravitation opened the era
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MONDAY, DECEMBER 12

9:00 a.m.  Introductions and Remarks - J. Armstrong, M. Bardon
9:30 a.m.  Oversight Review of the NSF Elementary Particle Physics Program
           NSF Role in Elementary Particle Physics - D. Berley
10:00 a.m. DOE and Elementary Particle Physics - W. Wallenmeyer
10:30 a.m. Report of Subcommittee for Review of NSF Elementary Particle Physics Program - R. Schwitters
11:00 a.m. Discussion of Oversight Review
12:00 Noon Lunch
1:30 p.m.  Cornell Upgrading - B. McDaniel
2:30 p.m.  Discussion of Elementary Particle Physics Program and Related Issues
6:00 p.m.  Adjourn

TUESDAY, DECEMBER 13

9:00 a.m.  Funding Pressures for FY 1984/1985 and Planning of Major Projects in Physics Division - M. Bardon
9:30 a.m.  University of Illinois Microtron - L. Cardman
10:30 a.m. MIT/Caltech Laser Interferometer Project - R. Drever/R. Weiss
12:00 Noon Lunch
1:30 p.m.  Report of Review Subcommittee - R. Schwitters
2:00 p.m.  Discussion of Long Range Plans
3:00 p.m.  Discussion with NSF Director, E. Knapp
3:30 p.m.  Continuation of Long Range Plan Discussion and Other Committee Business
6:00 p.m.  Adjourn
ADVISORY COMMITTEE FOR PHYSICS

(Chairman: Dr. John A. Armstrong)

Dr. Ralph D. Amado
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104
(215, 898-8147)

Dr. John A. Armstrong
IBM Corporation
T. J. Watson Research Center
PO Box 218, Dept. 460, Location 16-112
Yorktown Heights, New York 10598
(914, 945-1228)

Dr. Sam M. Austin
Department of Physics
and Astronomy
Michigan State University
East Lansing, Michigan 48824
(517, 353-7602)

Dr. Gordon A. Baym
Department of Physics
University of Illinois
Urbana, Illinois 61801
(217, 333-4363)

Dr. George B. Benedek
Department of Physics 13-2005
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
(617, 253-4828)

Dr. Peter G. Bergmann
Department of Physics
New York University
New York, New York 10003
(212, 598-7634)

Dr. Richard Blankenbecler
Stanford Linear Accelerator Center
Post Office Box 4349
Stanford, California 94305
(415, 854-3300 x2670)

Dr. Eugene D. Commins
Department of Physics
University of California
Berkeley, California 94720
(415, 642-2321)

Dr. Stanley Deser
Department of Physics
Brandeis University
Waltham, Massachusetts 02254
(617, 647-2845)

Dr. William A. Fowler
W. K. Kellogg Radiation Laboratory 106-38
California Institute of Technology
Pasadena, California 91125
(213, 356-4272)

Dr. Lee G. Pondrom
Department of Physics
University of Wisconsin
Madison, Wisconsin 53706
(608, 262-2284)

Dr. Roy F. Schwitters
*Fermi National Accelerator Laboratory
Post Office Box 500
Batavia, Illinois 60510
(312, 840-4590 FTS: 370-4590)
*TEMPORARY, 1982-83

Dr. John F. Waymouth
Laboratory Director
Lighting Products Group
GTE Products Corporation
Sylvania Lighting Center
Danvers, Massachusetts 01923
(617, 777-1900)

 Nóvember 1983
The committee is impressed with the long-range scientific potential of gravitational wave detection. It will not only test our basic understanding of gravitation but provide an entirely new window on the Universe. We have considered the major interferometric laser detection systems now being developed by the Caltech and MIT groups. As we have noted, not only is this an outstanding scientific opportunity, but the Foundation is the only source of support for ground-based gravitational physics.

As with any attempt at a qualitative advance, there are risks. Nevertheless, here the uncertainties, involving both the magnitude of the signals to be detected and the large extrapolation of known experimental technique inherent in the proposed scale.
Interferometers

*international network*

Simultaneously detect signal (within msec)

LIGO, GEO, Virgo, TAMA

detection confidence
locate the sources
de-compose the polarization of gravitational waves
LIGO Observatory Facilities

**LIGO Hanford Observatory [LHO]**
- 26 km north of Richland, WA
- 2 km + 4 km interferometers in same vacuum envelope

**LIGO Livingston Observatory [LLO]**
- 42 km east of Baton Rouge, LA
- Single 4 km interferometer
GEO Interferometer Configuration
Measurement challenge

- Needed technology development to measure:

\[ h = \frac{\Delta L}{L} < 10^{-21} \]

\[ \Delta L < 4 \times 10^{-18} \text{ meters} \]
NOISE SOURCES

Noise Terms Influencing the Strain Measurement
* Shot (Poisson) Noise
  Light Amplitude Noise
  Laser Frequency Fluctuations
  Scattering of Light by
    1) Moving Sources
    2) Stationary Sources
  Laser Beam Position and Angle Jitter
  Residual Gas Column Density Fluctuations

Fluctuation Forces Moving the End Points
* Seismic Noise
* Thermal Noise in the Suspension Elements
  Thermal Noise Driving the Mirror Normal Modes
  Optical / Mechanical Imbalance Radiation Pressure Force
  “Radiometer” Force Driven by Light Amplitude Noise
  Fluctuating External Gravitational Gradients
  Fluctuating “Patch” Electric Fields
  Fluctuating Magnetic Fields Acting on Iron Impurities
  Cosmic Ray Muons
  The “Naive” Quantum Limit
* Important Terms Influencing Initial Sensitivity Goals
FRINGE SENSING

\[ h = \frac{x}{L} \sim \frac{\lambda}{L_b \sqrt{N_t}} \]

- Wavelength: \(1 \times 10^{-6} \text{ m}\)
- Arm length: 4000 m
- Equivalent # of passes = 100
- Number of quanta/second at the beam splitter
- 300 watts at beam splitter = \(10^{21}\) identical photons/sec

\[ h = 6 \times 10^{-22} \quad \text{integration time} = 10^{-2} \text{ sec} \]
Quantum Noise in the Michelson Interferometer

\[ F_{rad} = (E_{coh} + E_{incA} + E_{incS})^2 \]

\[ \Delta F_{rad} = 4E_{incA}E_{coh} \]

\[ F_{rad} = (E_{coh} - E_{incA} + E_{incS})^2 \]

Prof Robert Pound smelled a rat in 1975
Carlton Caves got it right in 1980
PENDULUM THERMAL NOISE

Pendulum Brownian motion
Dissipation leads to fluctuations

\[ \tau = \text{coherence or damping time} = Q \times \text{period of oscillator} \]

Exchange with surroundings:

\[ E(\text{thermal}) = \frac{kT \cdot t}{\tau} \]

Large \( \tau \) => smaller fluctuations

Mechanisms
velocity dependent – viscous
position dependent lag – structure
thermo-elastic - Zener
Phase noise from molecular scattering

\[ E_{\text{scat}} = -i p E_{\text{beam}} \]
Feedback Control Systems

- Array of sensors detects mirror separations, angles
- Signal processing derives stabilizing forces for each mirror, filters noise
- 5 main length loops shown; total ~ 25 degrees of freedom
- Operating points held to about 0.001 Å, .01 μrad RMS
- Typ. loop bandwidths from ~ few Hz (angles) to > 10 kHz (laser wavelength)

example: cavity length sensing & control topology
Classes of sources and searches

- **Compact binary inspiral: template search**
  - BH/BH
  - NS/NS and BH/NS
- **Low duty cycle transients: wavelets, T/f clusters**
  - Supernova
  - BH normal modes
  - Unknown types of sources
- **Externally triggered searches**
  - Gamma bursts
  - EM transients
- **Periodic CW sources**
  - Pulsars
  - Low mass x-ray binaries (quasi periodic)
- **Stochastic background**
  - Cosmological isotropic background
  - Foreground sources: gravitational wave radiometry
Gravitational waves from compact binaries

- LIGO is sensitive to gravitational waves from binary systems with neutron stars & black holes
  - Waveforms depend on masses and spins.
    - **Binary neutron stars**
      - Estimates give upper bound of 1/3 yr in LIGO S5
    - **Binary black holes**
      - Estimates give upper bound of 1/yr in LIGO S5

![Diagram of gravitational waves and binary systems](image)

P. Brady
Binary Neutron Stars: S5 Search (Preliminary)

S2 Horizon Distance
1.5 Mpc

Optimum polarization and orientation SN > 8

Averaged over polarization and sky position

P. Brady, G. Gonzalez
Binary Black Holes
S5 Search

- 3 months of S5 analyzed
- Horizon distance versus mass for

Average over run 130Mpc
1 sigma variation

binary black hole horizon distance

binary neutron star horizon distance

P. Brady  APS Meetir
Burst search: a time-frequency method

- Compute time-frequency decomposition in a Fourier or wavelet basis
- Threshold on power in a pixel; search for clusters of pixels
- Basic assumption: multi-interferometer response consistent with a plane wave-front incident on network of detectors:
  - use temporal coincidence of the 3 interferometer’s ‘loudest pixels’
  - correlate frequency features of candidates (time-frequency domain analysis)
  - check consistency of the signal amplitude
  - test the list of coincident event candidates for waveform consistency (correlation) between signals from three LIGO interferometers.
- End result of analysis pipeline: number of triple coincidence events
Preliminary detection efficiency and upper limit reach for initial part of S5

\[ h_{rss} \equiv \sqrt{\int (|h_+ (t)|^2 + |h_\times (t)|^2) \, dt} \]
Possible supernova explosion model

  - Axisymmetric simulations with non-rotating progenitor
  - In-falling material eventually drives oscillations of the core
  - Hundreds of ms after the bounce and lasting several hundred ms
GRB 070201

- Feb 1, 2007: short hard $\gamma$ burst
- Observed by five spacecraft
- Location consistent with M31 spiral arms (0.77 Mpc)
- At the time of the event, both Hanford instruments were recording data (H1, H2), while others were not (L1, V1, G1)
Inspiral and burst analyses

- On source data: 180s around GRB
- Off source, for background est.
  - inspiral: -14h, +8h
  - burst: -1.5h, +1.5h
- Some (.9%) off source data excluded, based on data quality cuts obtained from playground studies (e.g. excess seismic noise, digital overflows, hardware injections of fake signals)
- Assume gravitational waves travel at the speed of light
Inspiral search - GRB 070201

- Matched template analysis, \(1M_\odot < m_1 < 3M_\odot\), \(1M_\odot < m_2 < 40M_\odot\)
- \(H1 \sim 7200\) templates, \(H2 \sim 5400\) templates, obtain filter SNR
- Require consistent timing and mass parameters between \(H1\), \(H2\)
- Additional signal-based tests: \(\chi^2\), and \(r^2\) veto
- SNR and \(\chi^2\) combined into effective SNR \(\rho_{\text{eff}}\)
- No gravitational wave candidates found
- Compact binary in M31 excluded at 99% confidence
Summary of Periodic Sources and Detection Sensitivity

M.A. Papa
Isotropic Stochastic Background

\[ \Omega_{GW}(f) = \frac{f}{\rho_c} \frac{d\rho_{GW}}{df} \]

**S4 result**
(astro-ph/0608606):

\[ \Omega_{GW} < 6.5 \times 10^{-5} \]

Bayesian 90% U.L.

Fake signal injected into LHO, LLO 4km instruments, then recovered
Gravitational Wave “Radiometer”

S4 Result: Limit on Point Sources

$H_{90\%} = (0.85 - 6.1) \times 10^{-48} \text{ Hz}^{-1}$
Program of detector improvements

- **Major steps between initial and advanced LIGO**
  - Increase laser input power 10 to 180 watts in stages
  - Incorporation of an output mode cleaner
  - Output optics and electro-optics chain in vacuum
  - DC (carrier offset) “modulation” technique
  - Reduction in thermal noise
    - Steel wire to fused quartz ribbon suspension elements
    - Lower mechanical dissipation optical coatings
    - Larger fused silica test masses: 10 kg to 40 kg
  - Improved active seismic isolation – extend sensitivity to 15Hz
  - Tunable dual recycling interferometer configuration
  - Quantum limited operation over significant band
Horizon Distance Mpc

<table>
<thead>
<tr>
<th>curve</th>
<th>NS/NS</th>
<th>10/10BH</th>
<th>30/30BH</th>
<th>60/60BH</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 S5</td>
<td>32</td>
<td>160</td>
<td>169</td>
<td>57</td>
</tr>
<tr>
<td>L1 S5</td>
<td>31</td>
<td>157</td>
<td>215</td>
<td>83</td>
</tr>
<tr>
<td>SRD</td>
<td>34</td>
<td>170</td>
<td>219</td>
<td>127</td>
</tr>
<tr>
<td>Rana S6</td>
<td>71</td>
<td>349</td>
<td>443</td>
<td>208</td>
</tr>
<tr>
<td>SUM</td>
<td>92</td>
<td>450</td>
<td>638</td>
<td>209</td>
</tr>
</tbody>
</table>

Detection Rate relative to SRD

<table>
<thead>
<tr>
<th>curve</th>
<th>NS/NS</th>
<th>10/10BH</th>
<th>30/30BH</th>
<th>60/60BH</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 S5</td>
<td>0.84</td>
<td>0.83</td>
<td>0.46</td>
<td>0.09</td>
</tr>
<tr>
<td>L1 S5</td>
<td>0.79</td>
<td>0.79</td>
<td>0.94</td>
<td>0.28</td>
</tr>
<tr>
<td>Rana S6</td>
<td>9.1</td>
<td>8.7</td>
<td>8.2</td>
<td>4.4</td>
</tr>
<tr>
<td>SUM</td>
<td>20</td>
<td>19</td>
<td>23</td>
<td>4.5</td>
</tr>
</tbody>
</table>

NS/NS detection rates using 100 NS/NS mergers per Myr in MWEG and 0.01 MWEG/Mpc$^3$

H1 S5 => 0.012/year
L1 S5 => 0.011/year
SRD => 0.014/year
Rana S6 => 0.13/year
SUM => 0.28/year

Strain sensitivity initial, enhanced and advanced LIGO

- INIT LIGO
- SRD
- LIGO
- LIGO-HO
- advligo NS/NS
- enhanced initial LIGO
- advligo narrow band tuning

- grav
- grad
- suspension thermal
- coating thermal
- tuning
- advligo low freq
Advanced LIGO modes of operation

<table>
<thead>
<tr>
<th>Mode</th>
<th>NS-NS Range</th>
<th>BH-BH Range</th>
<th>$P_{in}$</th>
<th>$T_{SRM}$</th>
<th>$\phi_{SRC}$</th>
<th>$h_{RMS}$, $10^{-22}$ (band)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>143 Mpc</td>
<td>1.28 Gpc</td>
<td>25 W</td>
<td>100%</td>
<td>-</td>
<td>0.57 (40–140 Hz)</td>
</tr>
<tr>
<td>1a</td>
<td>145 Mpc</td>
<td>1.48 Gpc</td>
<td>25 W</td>
<td>20%</td>
<td>0 deg.</td>
<td>0.75 (120–220 Hz)</td>
</tr>
<tr>
<td>1b</td>
<td>180 Mpc</td>
<td>1.32 Gpc</td>
<td>125 W</td>
<td>20%</td>
<td>0 deg.</td>
<td>0.39 (265–365 Hz)</td>
</tr>
<tr>
<td>2</td>
<td>186 Mpc</td>
<td>1.13 Gpc</td>
<td>125 W</td>
<td>20%</td>
<td>11 deg.</td>
<td>0.30 (285–385 Hz)</td>
</tr>
<tr>
<td>3</td>
<td>170 Mpc</td>
<td>1.68 Gpc</td>
<td>20 W</td>
<td>20%</td>
<td>20 deg.</td>
<td>0.47 (155–255 Hz)</td>
</tr>
</tbody>
</table>
Projections for Advanced LIGO: sensitivity and sources
The Gravitational-Wave Spectrum

![Gravitational-Wave Spectrum Diagram](image)

- Coalescence of Massive Black Holes
- Resolved Galactic Binaries
- Unresolved Galactic Binaries
- NS-NS and BH-BH Coalescence
- SN Core Collapse

Frequency (Hz)

Gravitational Wave Amplitude
Mission Concept
Spacecraft Orbits

- Spacecraft orbits evolve under gravitational forces only
- Spacecraft fly “drag-free” to shield proof masses from non-gravitational forces
Massive Black Holes in Merging Galaxies

Gravitational Wave Amplitude $h$

Frequency (Hz)

$10^{10} M_{\odot}$

$10^{10} M_{\odot}$

Binary Confusion Noise Threshold Estimate:
1 yr, S/N=5

LISA Instrumental Threshold

1992

10 light days

Hubble Space Telescope

R. Genzel
Power and signal recycling configuration