Gravitational wave astronomy
past, present and future

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High-energy gamma-ray experiments at the dawn of gravitational wave astronomy
Pisa, 18 October 2016
Gravity is a manifestation of spacetime curvature induced by mass-energy.

\[
G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}
\]

"Spacetime tells matter how to move; matter tells spacetime how to curve”

(John Archibald Wheeler)
1916

Über Gravitationswellen.
Von A. Einstein.

Die wichtige Frage, wie die Auslautung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiewerke vor mir behandelt worden. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen be-
dauernlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränkte ich mich auch hier auf den Fall, daß das betrachtete zeitabhängige Kontinuum sich von einem "galileischen" nur sehr wenig unterscheidet. Um für alle Indizes
\[ g_{\mu\nu} = g^{\mu\nu} + h_{\mu\nu} \]  
(1)

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable \( x^0 \) rein imaginär, indem wir
\[ x^0 = i t \]

setzen, wobei \( t \) die "Lichtzeit" bedeutet. In \( i \) ist \( \delta_{\mu\nu} = \iota \) bzw. \( \delta_{\mu\nu} = c \), je nachdem \( \mu = \nu \) oder \( \mu \neq \nu \) ist. Die \( \gamma_{\mu\nu} \) sind gegen \( t \) kleine Größen, welche die Abweichung des Kontinuums vom Freien darstellen; sie bilden einen Tensor vom zweiten Rang gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsungleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen Feldgleichungen
\[ -\sum \frac{\partial}{\partial x^\mu} \left( \frac{\partial T_{\nu\kappa}}{\partial x^\mu} \right) + \sum \frac{\partial}{\partial x^\mu} \left( \frac{\partial h_{\nu\kappa}}{\partial x^\mu} \right) + \sum \frac{1}{c^2} \left( \frac{\partial T_{\nu\kappa}}{\partial t} \right) = -\sum \left( T_{\nu\kappa} - \frac{1}{2} g_{\nu\kappa} \right). \]

Having solutions
\[ h_{\mu\nu}(t - x/c) \]

Spacetime perturbations, propagating in vacuum like waves, at the speed of light: gravitational waves.
Gravitational waves are strain in space propagating with the speed of light

Main features

• 2 transversal polarization states

• Associated with massless, spin 2 particles (gravitons)

• Emitted by time-varying quadrupole mass moment
  no dipole radiation because of conservation laws

\[
- \frac{dE}{dt} = \frac{2G}{3c^3} \left( \ddot{d} \right)^2 + \frac{G}{45c^5} \left( \dddot{Q} \right)^2 + ...
\]

\[
\dot{d} = \sum_i m_i \dot{x}_i \Rightarrow \ddot{d} = 0 \quad Q_{ij} = \int \rho x_i x_j d^3 x
\]

\[
h_{ij}(t) = \frac{2G}{rc^4} \dddot{Q}_{ij}(t - r/c)
\]
• No laboratory equivalent of Hertz experiments for production of GWs

Luminosity due to a mass $M$ and size $R$ oscillating at frequency $\omega \sim v/R$:

$$L = \frac{2G}{5c^5} \langle \ddot{Q}^2 \rangle \approx \frac{GM^2v^6}{R^2c^5}$$

$Q \approx MR^2 \sin \omega t$

$M=1000$ tons, steel rotor, $f = 4$ Hz $\quad L = 10^{-30}$ W

Einstein: “... a practically vanishing value...”

Collapse to neutron star $1.4$ $M_\odot$ $\quad L = 10^{52}$ W

$h \sim W^{1/2}d^{-1}$; source in the Galaxy $h \sim 10^{-18}$, in VIRGO cluster $h \sim 10^{-21}$

Fairbank: “...a challenge for contemporary experimental physics..”
\[ A = \frac{\kappa}{24\pi} \sum_{aB} \left( \frac{\partial^3 J_{aB}}{\partial t^3} \right)^2. \]

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor \( \frac{1}{c^4} \) hinzutreten. Berücksichtigt man außerdem, daß \( \kappa = 1.87 \cdot 10^{-27} \), so sieht man, daß \( A \) in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

“…..in any case one can think of \( A \) will have a practically vanishing value.”
Gravitational Waves
Gravitational Waves

Comparison with electromagnetic waves

Horizontal polarization

Vertical polarization

Plus polarization

Cross polarization

The so-called “electromagnetic theory of light” has not helped us hitherto . . . it seems to me that it is rather a backward step . . . the one thing about it that seems intelligible to me, I do not think is admissible . . . That there should be an electric displacement perpendicular to the line of propagation’

Lord Kelvin
\[ F = -kx \]

\[ F \Leftrightarrow T_{\mu\nu} \]

\[ x \Leftrightarrow G_{\mu\nu} \]

\[ k \Leftrightarrow \frac{c^4}{8\pi G} \]

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

\[ c = 299,792,458 \ \text{m/s} = 3 \times 10^8 \ \text{m/s} \]

\[ G = 6,000,000,000,066.7 \ \text{m}^3/\text{kg s}^2 = 6.67 \times 10^{-11} \ \text{m}^3/\text{kg s}^2 \]

\[ k \approx 10^{45} \ \text{kg/s}^2 \quad \text{STIFF!} \]
GW OBJECTIVES

FIRST DETECTION
- test Einstein prediction

\[ G = \frac{8\pi G}{c^4} \, T \]

ASTRONOMY & ASTROPHYSICS
- look beyond the visible,
- understand Black Holes,
- Neutron Stars and supernovae
- understand GRB

COSMOLOGY
- the Planck time:
- look as back in time as theorist can conceive
Cosmic Microwave Background
Polarization B Modes

Gravitational Wave Spectrum

Frequency Hz

Primeval gravitational waves from inflationary epoch
Measured at epoch of recombination $z \sim 1000$ and reionization $z \sim 6$

Pulsar Timing
Massive BH coalescences
Small mass/BH infalls
White dwarf binaries in our galaxy

Space-based Interferometers

Ground-based Interferometers
Compact binary coalescences: neutron stars and black holes
Asymmetric pulsar rotations

Supermassive BH coalescences
Isotropic GW background from unresolved sources
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

Information
Inner detailed dynamics of supernova
See NS and BH being formed
Nuclear physics at high density

SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

Information
Neutron star locations near the Earth
Neutron star Physics
Pulsar evolution

COALESCING BINARIES.
Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance.

Information
Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity

STOCHASTIC BACKGROUND.
Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

Information
Confirmation of Big Bang, and inflation
Unique probe to the Planck epoch
Existence of cosmic strings
can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.

Now the Newtonian equation corresponding to (14.2) is

\[
\frac{\partial^2 \eta^a}{\partial \tau^2} + \frac{\partial^2 \eta^b}{\partial x^a \partial x^b} = 0
\]  

(14.3)

It is interesting that the empty-space field equations in the Newtonian and general relativity theories take the same form when one recognizes the correspondence \( R_{\text{ab}}^a \sim \frac{\partial^2 \eta^a}{\partial \tau^2} \) between equations (14.2) and (14.3), for the respective empty-space equations may be written \( R_{\text{ab}}^a = 0 \) and \( \frac{\partial^2 \eta^a}{\partial \tau^2} = 0 \). (Details of this work are in the course of publication in *Acta Physica Polonica*.)

BONDI: Can one construct in this way an absorber for gravitational energy by inserting a \( \frac{\partial \eta}{\partial \tau} \) term, to learn what part of the Riemann tensor would be the energy producing one, because it is that part that we want to isolate to study gravitational waves?

PIRANI: I have not put in an absorption term, but I have put in a “spring.” You can invent a system with such a term quite easily.

LICHNEROWICZ: Is it possible to study stability problems for \( \eta \)?

PIRANI: It is the same as the stability problem in classical mechanics, but I haven’t tried to see for which kind of Riemann tensor it would blow up.
The main point of this presentation was that it is relative accelerations of neighboring free particles that are the physically meaningful (i.e., measurable) ways to observe gravitational effects. Pirani points out the transparent connection between the equation of geodesic deviation and Newton's Second Law, as long as one identifies $R_{ab0}$ with the second derivative of the Newtonian potential (i.e., as the tidal field.)

To make sure everyone sees how important and simple this is, he remarks, “By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor”.

*from: P. Saulson, Gen Relativ Gravit (2011) 43:3289–3299*
Joe Weber, co-inventor of the maser, was a U Md professor, on sabbatical in 1956-57 with John Wheeler at Princeton.

At the Chapel Hill conference in Jan 1957, they heard the key talk by Pirani that clarified that GW’s were real, because they could (in principle) be detected.
• GWs are detectable in principle
  The equation for geodetic deviation is the basis for all experimental attempts to detect GWs:
  \[
  \frac{d^2 \delta l^j}{dt^2} = -R_{jokol}^k = \frac{1}{2} \frac{\partial^2 h_{jk}}{\partial t^2} l^k
  \]

• GWs change (\(\delta l\)) the distance (l) between freely-moving particles in empty space.
  They change the proper time taken by light to pass to and fro fixed points in space.
  In a system of particles linked by non-gravitational (ex.: elastic) forces, GWs perform work and deposit energy in the system.

\[ h = \frac{\Delta L}{L} \]

\[ \ddot{x}(t) + \tau^{-1} \dot{x}(t) + \omega_0^2 x(t) = \frac{1}{2} \ddot{h}(t) \]
Weber’s bar

Weber’s detector embodied Pirani’s gedankenexperiment.

It was a cylinder of aluminum, each end of which is like a test mass, while the center is like a spring. PZT’s around the midline absorb energy to send to an electrical amplifier.
Weber invented us from scratch

It was an act of genius (and/or madness) to transform a *gendankenexperiment* into a working apparatus and an observing program.

Along the way, Weber developed:

- Sensitivity calculation and noise analysis
- Thermal noise minimization by high $Q$
- Seismic isolation
- Coincidence for background rejection
- Time slides for background estimation
- Inverse False Alarm Rate detection statistic
Weber started seeing things

In 1969, Weber made his first of many announcements that he was seeing coincident excitations of two detectors.

FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.
Acoustic bar GW Detector groups

1965-1975
Room T bars
- Bell Labs
- Frascati
- Glasgow
- IBM
- Rochester
- Max Planck
- Rome

1975-1990+
Cryogenic bars
- Frascati
- Louisiana
- Moscow
- Perth
- Rochester
- Stanford

2000 -
Spherical cryogenic detectors
- Brazil
- Netherlands

A. Tyson  W. Hamilton  P. Michelson
Since the pioneering work of Joseph Weber in the ‘60, the search for Gravitational Waves has never stopped, with an increasing effort of manpower and ingenuity:

60’: Joe Weber pioneering work
90’: Cryogenic Bars

1997: GWIC was formed
GWIC thesis prize named after Stefano Braccini

2000’ - Large Interferometers
Experimental gravitational physicists are heirs to several great traditions:

- High precision mechanical experiments (Cavendish, Eotvos, Dicke..) detection of weak forces applied on mechanical test bodies

- High precision optical measurements (Michelson, laser developers…)

- Operation of ultraprecise e-m measurement systems (microwave pioneers of World War II)

- Low temperature physics (K. Onnes) superfluids and superconductors technology
Global Network of Detectors
BeCer seismic isolation

Higher power laser

Better test masses and suspension

Better seismic isolation
BeCer seismic isolation

Higher power laser

Better test masses and suspension

Better seismic isolation
ADVANCED DETECTORS TIMELINE

foreseen at the end of 2015

Slots for science runs and commissioning/upgrades will be defined in a coordinated way.
GW150914: the signal

- Top row left – Hanford
- Top row right – Livingston
- Time difference ≈ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)
- Third Row – residuals
- Bottom row – time frequency plot showing frequency increases with time (chirp)
GW150914: Estimated Strain Amplitude

\[ M = \left( \frac{m_1 m_2}{m_1 + m_2} \right)^{3/5} = \frac{c^3}{G} \left[ \frac{5}{96} \pi^{8/3} f^{-11/3} f \right]^{3/5} \]

- Numerical relativity models of black hole horizons during coalescence
- Effective black hole separation in units of Schwarzschild radius \((R_s=2GM_{\text{tot}}/c^2=210\text{km})\); and effective relative velocities given by post-Newtonian parameter \(v/c = (GM_{\text{tot}} \pi f_{GW}/c^3)^{1/3}\)

### Binary Black Hole System
- \(M_1 = 36 \pm 5/4 \, M_{\odot}\)
- \(M_2 = 29 \pm 4 \, M_{\odot}\)
- Final Mass = 62 \pm 4 \, M_{\odot}
- distance=410 \pm160/-180 \, \text{Mpc} (\text{redshift } z = 0.09)
Nautilus - September 14, 2015
Use numerical simulations fits of black hole merger to determine parameters, we determine total energy radiated in gravitational waves is $3.0 \pm 0.5 \, M_\odot c^2$. The system reached a peak $\sim 3.6 \times 10^{56}$ erg, and the spin of the final black hole < 0.7

<table>
<thead>
<tr>
<th>Source Parameters for GW150914</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
</tr>
<tr>
<td>Final black hole mass</td>
</tr>
<tr>
<td>Final black hole spin</td>
</tr>
<tr>
<td>Luminosity distance</td>
</tr>
<tr>
<td>Source redshift, $z$</td>
</tr>
</tbody>
</table>
Plausible scenario for the operation of the LIGO-Virgo network over the next decade
<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>(E_{GW} = 10^{-2}M_\odot c^2) Burst Range (Mpc)</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
<th>% BNS Localized within 5 deg(^2)</th>
<th>% BNS Localized within 20 deg(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 60</td>
<td>40 – 80</td>
<td>0.0004 – 3</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60 – 75</td>
<td>80 – 120</td>
<td>0.006 – 20</td>
<td>5 – 12</td>
<td>–</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months</td>
<td>75 – 90</td>
<td>120 – 170</td>
<td>0.04 – 100</td>
<td>10 – 12</td>
<td>–</td>
</tr>
<tr>
<td>2019+</td>
<td>(per year)</td>
<td>105</td>
<td>60 – 85</td>
<td>0.2 – 200</td>
<td>8 – 28</td>
<td>–</td>
</tr>
<tr>
<td>2022+ (India)</td>
<td>(per year)</td>
<td>105</td>
<td>200</td>
<td>0.4 – 400</td>
<td>17</td>
<td>48</td>
</tr>
</tbody>
</table>
Sky areas broadly consistent with simply triangulation, and mostly cross-consistent.

Triangulation ring consistent with time delay of about $\sim 7$ ms.

Search area: 620 sq. degrees to cover.
Sky Locations of Gravitational-wave Events GW150914, GW151226 and Candidate LVT151012
Simulated Sky Locations of O1 Events and Candidate Including the Virgo Interferometer
Localization expected for a BNS system

The ellipses show 90% confidence localization areas, and the red crosses show regions of the sky where the signal would not be confidently detected.
Multi-Messenger Astronomy:
Gravitational Wave + Electromagnetic + Neutrinos
EINSTEIN TELESCOPE

✓ Design study of ET funded by the European Commission under FP7
  – interest primarily focused on the Infrastructure rather than on the detector and its technologies
  – The infrastructure should not limit the sensitivity of the future hosted detectors
    • Size
    • Environmental noises (seismic and NN)
  – ET absorbed and developed many concepts in GW detectors:
    • Underground and cryo-compatible facility, pioneered in Japan by CLIO and KAGRA
    • Triangular geometry, concept used in LISA
    • Xylophone configuration
From LISA to eLISA

- Savings mainly in weight, launch cost.
- Two active arms, not three;
- Smaller arms (1Gm, not 5Gm);
- Re-use LISA Pathfinder hardware;

eLISA

2029
THE GLOBAL PLAN

• Advanced Detectors (LIGO, VIRGO) will initiate gravitational wave astronomy through the detection of the most luminous sources - compact binary mergers.

• Third Generation Detectors (ET and others) will expand detection horizons and provide new tools for extending knowledge of fundamental physics, cosmology and relativistic astrophysics.

• Observation of low frequency gravitational wave with eLISA will probe the role of super-massive black holes in galaxy formation and evolution.
Every newly opened astronomical window has found unexpected results

<table>
<thead>
<tr>
<th>Window</th>
<th>Opened</th>
<th>1st Surprise</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>1609 Galilei</td>
<td>Jupiter's moons</td>
<td>1610</td>
</tr>
<tr>
<td>Cosmic Rays</td>
<td>1912</td>
<td>Muon</td>
<td>1930s</td>
</tr>
<tr>
<td>Radio</td>
<td>1930s</td>
<td>Giant Radio Galaxies</td>
<td>1950s</td>
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<tr>
<td></td>
<td></td>
<td>CMB</td>
<td>1964</td>
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<td></td>
<td></td>
<td>Pulsars</td>
<td>1967</td>
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<tr>
<td>X-ray</td>
<td>1948</td>
<td>Sco X-1</td>
<td>1962</td>
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<tr>
<td></td>
<td></td>
<td>X-ray binaries</td>
<td>1969 Uhuru</td>
</tr>
<tr>
<td>γ-ray</td>
<td>1961</td>
<td>GRBs</td>
<td>Late 1960s+ Vela</td>
</tr>
<tr>
<td>GW</td>
<td>2015</td>
<td>Binary BH mergers</td>
<td>2016</td>
</tr>
</tbody>
</table>