Gravitational Waves and Their Detection

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1. Overview of gravitational waves.
2. Can they give new physics information.
3. LIGO and LISA.
Gravitational Waves

- Gravitational radiation predicted in 1916 by Einstein as a consequence of general relativity.
- Experimental searches to directly detect gravitational waves using resonant bars began in 1960 (Joseph Weber at U of Maryland)
- Indirect observation of waves via back reaction on binary neutron star system
- First laser interferometer search began in 1972 (Robert Forward at Hughes Research Laboratories)
- LIGO is the most ambitious attempt so far to directly observe gravitational waves
# EM vs Gravitational Waves

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<th></th>
<th>EM Wave</th>
<th>Grav Wave</th>
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<tr>
<td>Nature</td>
<td>Oscillation of EM fields propagating thru spacetime</td>
<td>Oscillations of the fabric of spacetime</td>
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<td>Source</td>
<td>Acceleration of charge</td>
<td>Acceleration of mass</td>
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<td>Interaction with matter</td>
<td>Adsorption, scattering</td>
<td>Essentially none!</td>
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<td>Astrophysically relevant frequencies</td>
<td>&gt; 10 MHz</td>
<td>&lt; 10 KHz</td>
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<td>Polarization</td>
<td>Transverse, J=1</td>
<td>Transverse, quadrupole</td>
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- Waves push freely floating objects apart and together
  - \[ \frac{\Delta L}{L} = h(t) \]
- Local inertial frames do not mesh
- Like non-meshing of Cartesian coordinates on Earth's surface
  - Earth's curvature causes non-meshing
- Spacetime curvature causes inertial-frame non-meshing
- Gravitational waves are ripples of spacetime curvature
• Great richness to a wave’s spacetime curvature:
  
  – Heuristically:
    - Stretch and squeeze of space
    - Slowing and speeding of rate of flow of time
    - …
  
  – Measure stretch and squeeze with light beams

  - Does light wavelength get stretched and squeezed the same as mirror separation, so no effect is seen?
  - NO! Spacetime curvature influences light differently from mirror separations.
  
  – Mathematically:
    - Curvature described by rank-4 Riemann tensor, $R_{\alpha\beta\gamma\delta}$
Electromagnetic Radiation

In an inertial reference frame:
Positive and negative charge allows dipole radiation
Only positive mass exists, so dipole displacements are not allowed by conservation of momentum.

so quadrupole radiation is lowest order radiation multipole

Gravitational source from quadrupole deformation of a sphere
Sources of Gravitational Radiation

• Things that have a non-zero second derivative of the quadrupole moment
  – Coalescence of compact binaries:
    • Neutron stars, black holes, and combinations
  – Type II Supernovae
  – Asymmetric neutron stars
  – Rotational instabilities in neutron stars
  – Asymmetric black hole collapse.
• Stochastic background sources:
  • primordial radiation, phase transitions, cosmic strings
Polarization of gravitational waves

arrows show the direction of strain of "space-time"
Hulse-Taylor binaries: neutron stars with periods of 6 to 8 hours about common center.

Doppler effect modulates pulsar emission to that orbital period can be accurately measured.
How do these waves propagate

1. High frequency waves with wavelengths less than the radius of curvature of the background spacetime is the geometrical optics limit. The high frequency waves can be redshifted and gravitationally lensed like light.

2. If the wavelength ~ background spacetime curvature then it can be scattered by the spacetime curvature.

3. Absorption by matter is negligible and dispersion by interaction with matter negligible.

4. The spectrum of known and expected sources extends over 22 decades in frequency.
Amplitude / Strength of waves

Source: Mass M and size L with oscillatory period P

Quadrupole moment $\sim M L^2$

Higher multipoles will contribute by ($v/c$) to some power and hence will be relevant for strongly asymmetric sources.

For colliding Black Holes or Neutron Stars

amplitude $\sim 10^{-22}$
How a LIGO Interferometer Works

- Schematic description of detector:

\[ \Delta L = hL \lesssim 4 \times 10^{-16} \text{ cm} \]

\[ \lesssim 10^{-21} \quad 4 \text{ km} \]
- **First searches for GW’s:** 2002 to 2006 -- sensitivity where plausible to see waves
- **Upgrade to advanced interferometers:** ~2007; 3000 higher event rate
  - **new search:** 2008 ... -- sensitivity where should see rich waves from wide variety of sources
International Network of Interferometric Detectors

- Network Required for:
  - Detection Confidence
  - Waveform Extraction
  - Direction by Triangulation

![Diagram showing LIGO detectors in Hanford, WA, TAMA300 in Tokyo, GEO600 in Hanover, Germany, and VIRGO in Pisa, Italy]
LIGO: Initial Interferometers

- Have been installed (Hanford 4km, 2km; Livingston 4 km)
- Are being debugged; first search underway (at poor sensitivity)

\[ h_{\text{rms}} = h(f) \sqrt{f} \quad \text{10} \ h(f) \]

Square root of Spectral density of \( h(t) \) ["theory of random processes"]
LISA: Laser Interferometer Space Antenna

- Three “drag-free” spacecraft
- 5 million km separations
- 1 Watt laser, 30cm diameter telescopes
- Relative motions of spacecraft:
  \( \sim 1 \text{ million wavelengths/ sec} \)
- Light beams beat against each other (heterodyne detection);
  beat signal fourier analyzed
LISA: The Technical Challenge

- Monitor the relative motion of the satellites’ “proof masses”, 5 million kilometers apart, to a precision
  - $\sim 10^{-9}$ cm [in frequency band $f \sim 0.1 - 10^{-4}$ Hz ]
  - $\sim 10^{-5}$ of the wavelength of light
  - accelerations $\sim 10^{-16}$ g

- Guarantee that the only forces acting on the proof masses at this level are gravitational, from outside the spacecraft
LIGO: Scientific Goals

1. Open a new window onto the universe. This window is almost transparent to matter till big bang and directly probes the spacetime curvature.

2. Inspiralling and collisions of highly dense objects.

3. Waves from the Planck era which are amplified by inflation. This will also serve as a test of whether inflation is correct.

4. Phase transitions in the early universe.

5. Brane scenarios may tested through mesoscopic oscillations in the low frequency band.

** Other Detection techniques: Squeezed State detectors, Matter Wave interferometry