Binary Black Holes, Gravitational Waves, & Numerical Relativity

Part 1

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Connecting Quarks with the Cosmos
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The oldest science…

Most of the information we have about the Universe has come to us in the form of . . .

• Electromagnetic (EM) radiation
  – Visible light: naked eye observations, optical telescopes
  – Full EM spectrum: radio, IR, UV, visible, X-rays, Γ-rays

• Particle & nuclear astrophysics, neutrinos, cosmic rays.

These cosmic messengers provide a wealth of information, making astronomy one of the crowning glories of 20th century science….
Gravitation dominates the dynamics of the Universe...

- Grand Newtonian synthesis...
- Gravitational field – action at a distance
- Law of Universal Gravitation (1687)
- Fruitful legacy . . .
  - Solar system dynamics
  - Discovery of new planets, both solar and extra-solar
  - Motions of stars within galaxies
  - Motions of galaxies within clusters . . .

Isaac Newton (1642-1727)
Einstein’s new ideas about space and time….

Special relativity (1905)
- Space + time \rightarrow \text{spacetime}
- Speed of light is constant

General Relativity (1916)
- Spacetime is \textit{dynamic}
- Spacetime \textit{curvature} replaces concept of gravitational field
  - Presence of mass-energy causes spacetime to curve
  - Particles and light follow paths in curved spacetime

Albert Einstein (1879 – 1955)
Einstein’s legacy is proving remarkably fruitful…

• Expanding universe…
• Gravitational Lenses
  – caused by light traveling in curved spacetime
  – multiple images produced when massive object deflects light from more distant sources
Total gravitational collapse & black holes...

- Stellar black holes, having masses $M \sim \text{few } \times 10^2 \text{ } M_{\text{Sun}}$
  - Form via core collapse of some massive stars
  - if mass of remnant core $\sim 2 \text{ } M_{\text{Sun}}$ or larger $\rightarrow$ BH will form
  - BH may also form from fallback of gas onto NS $\rightarrow$ collapse
- Intermediate mass BHs (IMBHs) $M \sim \text{few } \times 10^2 \text{ } M_{\text{Sun}} - 10^4 \text{ } M_{\text{Sun}}$
  - form during hierarchical structure formation
  - in stellar clusters by successive mergers of lower mass BHs
Massive Black Holes...lurk at the centers of galaxies...

- First found in active galaxies
- Jets emanating from centers of active galaxies
  - result from accretion of gas onto central MBH
  - jet directed along spin axis

- Most galaxies believed to have central MBH
- MBH mass correlated with gas velocity dispersion
Massive Black Holes (MBHs)…

- Masses $M \geq 10^5 \, M_{\text{Sun}}$
Merging MBHs in merging galaxies...

Most galaxies merge one or more times

→ MBH binaries
Massive Black Hole binaries...

Abell 400
Separation ~ 7600 pc

NGC 6240
Sepn ~ 1000pc

0402+379
Separation ~ 7.3 pc
Black hole binaries are strong sources of gravitational radiation....
Gravitational Waves . . .

- Predicted by Einstein’s General Relativity
- Ripples in spacetime curvature that travel at velocity $v = c$
- Generated by masses w/ time changing quadrupole moments
- Carry energy and momentum & interact weakly with matter
  
  → carry info about deep, hidden regions in the universe

Provide powerful new tool to observe the universe…
The effects of gravitational waves have already been seen indirectly…

- GWs emitted by a binary carry away energy, orbit shrinks
- Hulse-Taylor binary pulsar PSR 1913+16
  - Orbital period decay agrees with predictions of GR to within the observational errors of < 1%
  - Nobel Prize 1993
The direct detection of gravitational waves will open a fundamentally new window on the universe...
Amplitudes of Gravitational Wave Sources . . .

• Characteristic amplitude

\[
h \sim \frac{G}{c^4} \frac{\ddot{Q}}{r} \sim \frac{R_{Sch}}{r} \frac{v^2}{c^2}
\]

– \( r \) = distance to source
– \( R_{Sch} = \frac{2GM}{c^2} \)
– \( Q = \) (trace-free) quadrupole moment of source
– \( v = \) characteristic nonspherical velocity in source

→ Strongest sources have large masses moving with velocities \( v \sim c \)

Estimate upper limits:

• 1.4 \( M_{\text{Sun}} \) NS at
  • \( r = 15 \) kpc, \( h \sim 10^{-17} \)
  • \( r = 15 \) Mpc, \( h \sim 10^{-20} \)
  • \( r = 200 \) Mpc, \( h \sim 10^{-21} \)
  • \( r = 3000 \) Mpc, \( h \sim 10^{-22} \)

• 2.5 \( \times 10^6 \) \( M_{\text{sun}} \) MBH at
  • \( r = 3000 \) Mpc, \( h \sim 10^{-16} \)
Effect of a passing gravitational wave.

- “Test particles” arrayed in a circle or ring
  - floating freely in spacetime, only gravitational disturbances
- GWs act transverse to direction of propagation
- A GW passes perpendicularly through the plane of this slide….
- Distorts the ring of particles… 2 polarization states
Detecting gravitational waves. . .

- Resonant mass detectors, laser interferometers
- Detector of length scale $L$
- A passing gravitational wave causes distortion of detector that produces a strain amplitude $h(t) = \Delta L/L$
- Source waveforms scale as $h(t) \sim 1/r$

(graphic courtesy of B. Barish, LIGO-Caltech)
Estimating Gravitational Wave frequencies . . .

- Natural frequency

\[ f_o \sim \left( \frac{\bar{\rho} G}{4\pi} \right)^{1/2} \sim \frac{\sqrt{3}}{4\pi} \left( \frac{GM}{R^3} \right)^{1/2} \]

- 1.4 M\text{Sun} NS, \( R = 10 \text{ km} \)
  \[ f_o \sim 2 \text{ kHz} \]

- 10 M\text{Sun} BH
  \[ f_o \sim 1 \text{ kHz} \]

- 2.5 x 10^6 M\text{Sun} MBH
  \[ f_o \sim 4 \text{ mHz} \]

- Binary orbital frequency

\[ f_{GW} = 2 f_{\text{orb}} = \frac{1}{\pi} \left( \frac{GM}{a^3} \right)^{1/2} \]

- \( M = M_1 + M_2, M_1 = M_2 \)
- \( a = \) separation

- NS/NS, \( a = 10 R \)
  \[ f_{GW} \sim 200 \text{ Hz} \]

- BH/BH, \( a = 10 M \)
  \[ f_{GW} \sim 100 \text{ Hz} \]

- MBH/MBH, \( a = 10 M \)
  \[ f_{GW} \sim 4 \times 10^{-4} \text{ Hz} \]
Early gravitational wave detectors.

• Resonant mass detectors
  – Pioneered by Joe Weber
  – Measure distortions of large metallic “bar”
  – Cryogenic to reduce noise in detector
  – Sensitive to resonant frequencies → narrow band
  – Spherical detectors proposed

The Allegro detector at LSU has its principal sensitivity at ~ 920 Hz
Modern ground-based GW detectors . . .

- Laser interferometers with kilometer-scale arms
  - LIGO: Hanford, WA, and Livingston, LA; \( L = 4 \text{ km} \)
  - VIRGO: PISA, \( L = 3 \text{ km} \)
  - GEO600: Hannover \( L = 600 \text{ m} \)
- Detect high frequency GWs in the band \( 10 \text{ Hz} \leq f_{GW} \leq 10^4 \text{ Hz} \)
- Typical sources: NS/NS, NS/BH, BH/BH, stellar collapse...
**LISA: Laser Interferometric Space Antenna**

- NASA/ESA collaboration
- detect *low frequency* GW
  \[10^{-4} \text{ Hz} \leq f_{\text{GW}} \leq 1 \text{ Hz}\]
- 3 spacecraft in equilateral triangle
  - orbits Sun at 1 AU
  - 20° behind Earth in its orbit
- arm length \(L = 5 \times 10^6 \text{ km}\)
- optical transponders receive & re-transmit phase locked light
- precision measurements:
  strain amplitude \(h = \Delta L/L < 10^{-20}\)
- LISA Pathfinder: launch 2011
  - ESA: LISA Test Package
  - NASA: ST-7
Gravitational Wave Spectrum...

- Complementary observations, different frequencies & sources...
The Gravitational Wave Spectrum

**Sources**
- Quantum fluctuations in the very early Universe
- Binary supermassive black holes in galactic nuclei
- Phase transitions in the early universe
- Black holes, compact stars captured by supermassive holes in galactic nuclei
- Binary stars in the galaxy and beyond
- Merging binary neutron stars and stellar black holes in distant galaxies; fast pulsars with mountains

**Wave Period**
- Age of the Universe
- Years
- Hours
- Seconds
- Msec

**Frequency (Hz)**
- $10^{-16}$
- $10^{-14}$
- $10^{-12}$
- $10^{-10}$
- $10^{-8}$
- $10^{-6}$
- $10^{-4}$
- $10^{-2}$
- 1
- $10^2$

**Detectors**
- Inflation Probe (NASA)
- Precision timing of millisecond pulsars (1982 - )
- LISA (ESA/NASA, 2010)
- Big Bang Obs (NASA)
- Geo, Ligo, Virgo, Tama (2002 - )
- Laser interferometers on Earth (also bar detectors)
Simulation of the gravitational wave sky....
A gallery of gravitational wave sources...
Supernovae... stellar explosions
Pulsars lurking in supernova remnants...
Cosmic strings, phase transitions and other exotic phenomena in the early universe...
Compact binaries...black holes, neutron stars, and white dwarfs
Compact stars falling into MBHs in the centers of galaxies…
Galaxies merge -> black holes merge -> LISA detects them
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<th>$10^{-44}$ s</th>
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Gravitational Waves . . .

*a new kind of cosmic messenger*

“Every time you build new tools to see the universe, new universes are discovered. Through the ages, we see the power of penetrating into space.”

-- David H. DeVorkin (paraphrasing Sir William Herschel)