Detection of the Stochastic Background of nHz Gravitational Radiation from Massive Black Holes with a Pulsar Timing Array

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**OUTLINE**

- The universe of coalescing Massive Black Hole binaries produces a stochastic spectrum of Gravitational Radiation at nanoHertz frequencies.
- Highly magnetized, rapidly rotating neutron stars – pulsars – provide ultra-stable, celestial clocks.
- The MBH stochastic spectrum of gravitational radiation can be detected in “short-wave” limit with a Pulsar Timing Array – a nanoHertz GW telescope.
Connections to Other Lectures

- **Tues:** Gravitational Radiation, A. Buonanno
- **Tues:** Gravity Wave Interferometers, G. Gonzalez
- **Tues:** LISA, S. Larson
- **Wed:** GR Tests with Pulsars, I. Stairs
- **Thu/Fri:** Black Holes, S. Hughes
- **Thu:** Role of Massive BHs in Structure Formation, T. Di Matteo
- **Fri:** Observations of Black Holes, A. Fabian
- **Fri:** Massive Black Hole in the Galactic Center, E. Quataert
References


• Focus Session: “Pulsar Timing Array – A Nanohertz Gravitational Wave Telescope” Center for Gravitational Wave Physics, Penn State; 05 Jul 21-23
  http://cgwp.gravity.psu.edu/events/PulsarTiming/program.shtml

Massive Black Holes
(E. Quataert, Fri)

- **Sagittarius A** – Black Hole with mass of 4 million Suns ($M_\odot$) in the center of our Milky Way galaxy.
- **NGC 4258** – mass of 30 million $M_\odot$, similar to many nearby galaxies.
- **Quasars and “Active” Galaxies** – jets formed by poorly understood processes; masses up to a few billion $M_\odot$. 
Massive Black Hole in Galaxy M84 (A. Fabian, Thu)

Red = Radio “Jet” Emission

White = Radio & Optical Emission from near MBH

Blue = Optical Galaxy Emission

Radio Galaxy 3C272.1 = M84 = NGC4374

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The Big Bang... and the Growth of Structures (T. Di Matteo, Thu)

1-10 Billion yrs: merger mania -- growth of current galaxies

0.1-1 Billion yrs: first small galaxies form

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Galaxy Mergers $\rightarrow$ Binary Massive Black Holes

- Many galaxies contain Massive Black Holes.
- All galaxies grow by mergers.
- When two galaxies with MBHs merge, the two holes will sink to a common center.
- Compact Massive Black Hole binaries are inevitable!
Evolution of MBH Binary

Galaxy Merger

Core Merger

Other Processes

Loss Cone Depletion

Stall?

GW Orbit Decay

Dynamical Friction

Observational Normalization

adapted from Blandford, Begelman, & Rees (1980)
Gravitational Radiation (A. Buonanno, Tues)

- Masses distort surrounding fabric of space.
- **Accelerating masses** radiate “distortions”, or “ripples”, in the fabric of space with dimensionless amplitude, $h(x,t)$. This *is* gravitational radiation, which propagates away at speed of light.
- A **Binary MBH** ten billion light years away with orbit of 5y will produce a distortion of space by just $0.0000000000000001$ (16 zeroes!).
Model Universe of MBHs

Ingredients:
- Binary GW formulation (Peters & Matthews, 1965)
- Galaxy mergers & MBH assembly vs redshift
- MBH demographics in galaxies
- Galactic dynamics & the “final parsec problem”
- Cosmological parameters relating distance, redshift, volume

⇒ Stochastic Background of MBH Binary GWs
(n.b., “Foreground” in case of primordial background)
Binary MBH GW Spectrum

Merger rate + Mass function + GWs:

\[ N(z, f, M_1, M_2) \, df \propto \varphi_1 \varphi_2 \, R(z) C[\Omega, z] \, \mathcal{M}^{-5/3} \, f^{-8/3} \, df/f \]

MBH Mass fn

Merger rate

Cosmology

GW Timescale

\[ h_c^2(f) = f \int dz \, dM_1 \, dM_2 \, h^2(z,M) \, N(z,f,M_1,M_2) \]
\[ = \left\langle \left( \frac{\mathcal{M}}{10^8 M_\odot} \right)^{5/3} \right\rangle \left( f/\text{yr}^{-1} \right)^{-4/3} I_h \]

(see also Phinney 2002)

\[ \mathcal{M} = (M_1 M_2)^{3/5} / (M_1 + M_2)^{1/5} \]

n.b., integral separates: \[ \varphi(M) f^{-8/3} I(z) \]

\[ I_h = \int \frac{R(z)}{R_0} \frac{dz}{E(z)(1+z)^{4/3}} \]

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Stochastic Gravitational Wave Background from Massive Black Hole Binaries

Begelman, Blandford & Rees (1980)
Rajagopal & Romani (1994)

~One Number: Amplitude!!
Recent Updates

- Wyithe & Loeb (0211556)
  - Global merger tree model

- Enoki et al (0404389)
  - From Halos --> Galaxies (baryons)

- Sesana et al (0401543, 0409255)
  - Some explicit MBH binary/galaxy dynamics, estimated 0.1 nHz cutoff

- Penn State Mtg: eccentric early history?
  http://cgwp.gravity.psu.edu/events/PulsarTiming/program.shtml
LIGO & LISA
(G. Gonzalez, Tue; S. Larson, Tue)

- **LIGO** – Laser Interferometer Gravity-Wave Observatory seeks ripples from coalescing binary neutron stars and other systems: milliseconds time scale (kiloHertz).

- **LISA** – Laser Interferometer Space Array seeks ripples from final stages of coalescing binary MBHs and other systems: minutes time scale (milliHertz).
Gravitational Wave Spectrum

- **CMB** Polarization: primordial (S. Church, Wed)

- **Pulsars**: MBH-MBH

- **LISA**: MBH-MBH + mBH-MBH (S. Larson, Tue)

**LIGO**: Nstar-Nstar
Pulsars (I. Stairs, Wed)

- **Rapidly rotating, highly magnetized neutron-rich stars.**
- **Neutron star** (at center) has a mass of the Sun and a radius of 10 km -- could fit within the ring road around the Washington (and if placed there, the entire federal bureaucracy would disappear in milliseconds!).
- “Closed” **dipole field** (**pink/acqua**) extends to 100 km in the fastest spinning pulsars, and to 500,000 km in the slowest and rotates rigidly with star.
- The **radio beam** (**yellow**) is driven by a voltage generated by the spinning field in conducting medium -- analogous to the spinning conductor in a fixed field common to most electric generators.
Pulsar Timing – Observations (I.S., Wed)

- Faint signals are detected against background noise.
- Need wide bandwidth & long integration on large telescopes.
- Low level of interference is increasingly important.
Pulsar Timing – Data Reduction

![Graph showing pulse phase vs. power with Start Time and Arrival Time marked.]

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The pulse arrival time at the telescope is referenced through the GPS System (left) to the USNO master clock ensemble in Wash., DC (below).

USNO time is itself referenced via GPS to a single *International Atomic Time*. And then the relativistic effects from the moving Earth are removed to approximate a clock at rest in the center of the solar system.
Pulsar Timing - Ephemeris
Pulsar Timing - Analysis (I.S., Wed)

- Model building
  - Spin: phase, period, slowing down rate
  - Astrometric parameters: sky position, motion, parallax
  - Orbital parameters (if in binary system): period, separation, phase, ..

- Residuals, \( R = \text{Observations} - \text{Model} \)
- Is model complete? Are residuals consistent with measurement errors? Or is “something” more needed?
Time Transfer Errors (D. Nice)
Ephemeris Errors (D. Nice)

Arecibo data from PSR J1713+0747 analyzed using latest DE 405 solar system ephemeris; Splaver et al. (2004).

PSR J1713+0747 analyzed using previous-generation DE 200 solar system ephemeris.

~1µs timing errors ⇔ 300 m errors in Earth position in inertial frame.
Interstellar Plasma “Weather”

Ramachandran et al. (2005)

column density of electrons: $DM = \int n_e(l) \, dl$
excess propagation time: $t \text{ (sec)} = DM / 2.41 \times 10^{-4} [f(MHz)]^2$
Pulsar Timing Array – B1937+21

Timing noise? Interstellar weather?
Pulsar Timing Array – 1713+0747

Splaver et al. (2004)
Arecibo data; no second derivative.
Timing noise?

Pre upgrade  Post upgrade

Year

(a)
Pulsar Timing Array – B1855+09
(Lommen et al. 2005)

NRAO Green Bank, 42m

Arecibo, 200m
Periodogram Analysis – PSR B1855+09
(Lommen et al. 2005)
Gravity Wave Detection

Gravity Wave Source: MBH Binary

Pulsar 1

Pulsar 2

Telescope

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The path of the radio signal from the pulsar to the Earth is a null path, so

\[ dt^2 - ds^2 = 0 \]

\[ \Rightarrow \quad dt^2 = (\eta_{ij} + h_{ij})dx^i dx^j = ds^2 \left( 1 + h_{ij} \frac{dx^i}{ds} \frac{dx^j}{ds} \right) \]

Approximate and integrate

\[ \int_p^e dt \approx \int_p^e ds + \frac{1}{2} \int_p^e h_{ij} \frac{dx^i}{ds} \frac{dx^j}{ds} ds \]

\[ \ell = s + \frac{1}{2} \hat{s}^i \hat{s}^j \int_p^e h_{ij} ds = s + \frac{1}{2} \hat{s}^i \hat{s}^j \left[ H_{ij}(e) - H_{ij}(p) \right] \]

where \( H_{ij}(t) \equiv \int h_{ij}(t) dt \).
So let’s get an observable that is proportional to the wave

\[
\frac{d(\Delta \ell)}{dt} = \frac{1}{2} \hat{s}^i \hat{s}^j \left\{ h_{ij} \left[ t - (1 + \hat{n} \cdot \hat{s})s \right] - h_{ij} [t] \right\}
\]

Gravitational waves are proportional to the time derivative of pulsar arrival time residuals.

Every pulsar in every direction has correlated timing noise due to this term. This allows a weighted correlation analysis to optimally use data from multiple pulsars.
Pulsar Timing
Limits on the
Stochastic
Gravitational Wave
Background from
Massive Black Hole
Binaries

Current limits

Next Generation Experiments

Predictions by Jaffe & Backer

Characteristic Strain \( [a_c / 10^{-15}] \)

Frequency \( f [\text{yr}^{-1}] \)
Pulsar Timing Array -- Two Basic All-Sky Analysis Techniques

Spherical Harmonic Decomposition

\[ R(t, \hat{r}) = \int \sum_{l,m} B_{lm}(\omega) Y_{lm}(\theta, \phi) e^{-i\omega t} d\omega \]
\[ B_{lm}(\omega) = \int R(t, \hat{r}(\theta, \phi)) Y_{lm}^*(\theta, \phi) e^{i\omega t} dt d\Omega \]

Burke 1975
Detweiler 1979
Jaffe & Backer 2003
Demorest et al. 2005

Two-point correlation

\[ C(\hat{r}_1, \hat{r}_2) = \frac{1}{T} \int_0^T R(t, \hat{r}_1) R(t, \hat{r}_2) dt \]

Hellings & Downs 1983
Jenet, Hobbs, Lee, & Manchester 2005

• N.b., clock error has monopole signature; ephemeris error has dipole signature; gravitational wave has >= quadrupole signature.
The Allen Telescope Array

SKA 2004
July 19, 2004
Summary

- **Massive Black Holes** (MBHs) exist in galaxies.
- Galaxy mergers leads to binary MBHs.
- MBH binaries produce **Gravitational Radiation**.
- LIGO/LISA are future detectors of gravitational waves, but...we might get there first with the **Pulsar Timing Array** GW telescope probe of the nanoHertz spectrum!