Multimessenger opportunities with Massive Black Hole Binaries

Alberto Sesana
(Universita` di Milano Bicocca)
OUTLINE

Dynamics of MBH binary (MBHB) formation and dynamics

emission from MBHBs: gravitational waves (GWs) and electromagnetic (EM) radiation

Multimessenger astronomy with LISA and Athena (and LSST/Rubin)

Multimessenger astronomy with pulsar timing arrays (PTAs)
Observational facts

1- In all the cases where the inner core of a galaxy has been resolved (i.e. in nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH for convenience) has been found in the centre.

2- MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

3- Quasars have been discovered at $z \sim 7$, their inferred masses are $\sim 10^9$ solar masses!

THERE WERE $10^9$ SOLAR MASS BHs WHEN THE UNIVERSE WAS $<1$Gyr OLD!!!

MBH formation and evolution have profound consequences for GW astronomy
Structure formation in a nutshell

(From de Lucia et al. 2006)

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

(Menou et al 2001, Volonteri et al. 2003)
Binaries inevitably form

(From de Lucia et al. 2006)

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

*Where and when do the first MBH seeds form?*
*How do they grow along the cosmic history?*
*What is their role in galaxy evolution?*
*What is their merger rate?*
*How do they pair together and dynamically evolve?*

(Menou et al 2001, Volonteri et al. 2003)
Mergers
MBHB dynamics (BBR 1980)
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(Bonetti+18
Ryu+18)

(Kahn+11,
Preto+11,
AS&Khan15,
Vasiliev+15)

(Hayasaki+07,
Cuadra+09,
Roedig+11,
AS+12...)

(Branch+18
Roedig+11
AS+12...)

GMW Orbit Decay

Other Processes

Loss Cone

Stall?

Triplet

TIME SCALE, |R/R| [years]

GW Orbit Decay

Stars

Gas

Dynamical Friction

Observational Normalization

RADIUS, R [parsec]
MBHB dynamics (BBR 1980)
But do we see them?

10 kpc: double quasars (Komossa 2003)

1 pc: shifted BL (Tsalmatzsa 2011)
accelerating BL (Eracleous 2012)

1 kpc: double peaked NL (Comerford 2013)

0.01 pc: periodicity (Graham 2015)

0.0 pc: -X-shaped sources (Capetti 2001)
displaced AGNs (Civano 2009)

10 pc: double radio cores (Rodriguez 2006)
Binaries in the gravitational wave landscape

- $10^6 M_\odot \times 10^{17} \, f < 10^{-2}$
- $10^9 M_\odot \times 10^{14} \, f < 10^{-6}$
- $10^8 M_\odot \times 10^{-14} \, f < 10^{-3}$
- $10^6 M_\odot \times 10^{21} \, f < 10^3$

frequency [Hz]
The Laser Interferometer Space Antenna (LISA Consortium 2017)

Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

Oberves the full inspiral/merger/ringdown

3 satellites trailing the Earth connected through laser links

Proposed baseline:
2.5M km armlength
6 laser links
4 yr lifetime (10 yr goal)
The LISA Consortium

- Now a thriving community: 1300+ among full and associate members
- Several working groups connecting to the community: astrophysics, fundamental physics, cosmology, waveforms
- Several working packages defining deliverables
- 2 consortium meetings/yr, LISA symposium every 2 years, dedicated WG meetings every year

https://www.lisamission.org/
**Associated electromagnetic signatures**

In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal (Phinney & Milosavljevic 2005). However, all simulations (hydro, MHD) showed significant mass inflow (Cuadra et al. 2009, Shi et al 2011, Farris et al 2014, Tang et al. 2018...)

**Simulations in hot gaseous clouds. Significant flare associated to merger** (Bode et al. 2010, 2012, Farris et al 2012)

**Simulations in disk-like geometry. Variability, but much weaker and unclear signatures** (Bode et al. 2012, Gold et al. 2014)

**Full GR force free electrodynamics** (Palenzuela et al. 2010, 2012)
\[ L_X \]  

Disc re-brightening? Jet?

\[ t = -\infty \quad t = -20 \text{ h} \quad t = 0 \]

\[ h_{gw} \]


Quasi-circular inspiral  
 Plunge and merger  
 Ringdown

Post-Newtonian techniques  
 Numerical relativity  
 Black hole perturbation methods
Opportunities for LISA-Athena (LSST/Rubin) synergies
**Athena Wide Field Imager (WFI)** (Rau+ 2015)

- X-ray telescope
- L2 ESA mission (~2030)

**LSST : Vera Rubin observatory** (Abell+ 2009)

- 2022+
- Optical telescope
- 9.6 square degree FoV
- m~24 within 30s pointings in several different filters
HOW CAN LISA AND ATHENA WORK TOGETHER?

About 1 month before:
LISA detects gravitational waves from supermassive black holes spiralling towards each other and calculates the date and time of the final merger, but the position in the sky is unknown.

2 weeks before:
As the inspiral phase progresses, the gravitational wave signal gets stronger; meanwhile, LISA collects more data as it moves along its orbit, providing a better localisation of the source in the sky.

1 week to several hours before:
LISA indicates a fairly large patch in the sky (around 10 square degrees) where the source is located, so that Athena can start scanning this region to look for the source with its Wide Field Imager (WFI).

A few hours before:
LISA locates the source to within a smaller portion of sky, roughly equal to the size of the Athena WFI field of view (0.4 square degrees); Athena stops scanning, and starts staring at the most likely position of the source, witnessing the final inspiral and merger of the black holes.

During and after the merger:
While LISA detects the gravitational wave 'chirp', Athena can observe any associated X-ray emission and might witness the onset of relativistic jets: if this happens, Athena and LISA may witness the birth of a new 'active galaxy'.

#Space19plus #AnsweringTheBigQuestions
Athena pre-pointing only possible for very low z sources
-LSST/Rubin more suitable for tracking inspiral periodicity (but optical)

(Mangiagli+ 2020, Piro+ in prep.)
1/5 of the observable volume of the universe.

Universe was 2 Gyr old.
Why multimessenger?

- Cosmology and cosmography at high $z$
- Study of accretion on MBHs with known mass and spins
- Study of the interplay between MBHs and gas (torques, disk structure, disk models)
- Host galaxy, Jet launches, Quasar birth ...

Example of possible eLISA cosmological data

Courtesy of N. Tamanini
Binaries in the gravitational wave landscape

- 10^6 M_☉ @ 10 Gpc, h ≈ 10^{-17}, f < 10^{-2}
- 10^9 M_☉ @ 1 Gpc, h ≈ 10^{-14}, f < 10^{-6}
- 10 M_☉ @ 100 Mpc, h ≈ 10^{-21}, f < 10^3

Characteristic amplitude

Frequency [Hz]
**Pulsar timing**

Pulsars are neutron stars seen through their regular radio pulses.

Pulsar timing is the art of measuring the time of arrival (ToA) of each pulse and then subtracting off the expected time of arrival given by a theoretical model for the system.

1. Observe a pulsar and measure the ToAs
2. Find the model which best fits the ToAs
3. Compute the timing residual $R$

$$R = \text{ToA} - \text{ToA}_m$$

If the timing solution is perfect (and observations noiseless), then $R=0$. $R$ contains all uncertainties related to the signal propagation and detection, plus the effect of unmodelled physics, like (possibly) gravitational waves.
Incoherent superposition of sinusoids

\[ h_c(f) = A \left( \frac{f}{\text{yr}^{-1}} \right)^{-2/3} \]

Simulated signal

Actual data

(Courtesy of PPTA)
Resolvable sources (AS et al 2009)

*It is not smooth
*It is not Gaussian
*Single sources might pop-up
*The distribution of the brightest sources might well be anisotropic
Finding the right galaxy

In general, PTA cannot break the distance-mass degeneracy \((A \sim M^{5/3}/D)\)

\[
A = 4 \left( \frac{GM_\odot}{\pi f} \right)^{5/3} \frac{\sin^3(\phi)}{D_1}
\]

Sky localization is tens of deg\(^2\) so tens of thousands of potential host galaxies

An individual PTA source must be massive and/or nearby → Only several tens of credible candidates (Goldestein et al 2019)
Associated electromagnetic signatures PTA

MBH binary + circumbinary disk

A variety of possibilities:

Optical/IR dominated by the outer disk: Steady/modulated?

UV generated by inner streams/minidisk: periodic variability?

X rays variable from periodic shocks or intermittent corona?

Variable broad emission line in response to the varying ionizing continuum?

Double fluorescence lines?

Example: variability (AS+ 2012)

Streams feed the inner minidisk extremely intermittent mass inflow.

Applying this model to a typical MBH binary population we get ~100 sources at the eRosita flux limit.
The future

MeerKAT, South Africa (2017)
The future

Square Kilometre Array (SKA, 2021+)
**Doggybag**

**MBHBs:**

- are expected to form in the aftermath of galaxy mergers.

- Their dynamics is still a matter of active research, but binaries should form and coalesce within an Hubble time (reference figure: 10/yr).

- Are the loudest GW sources in the Universe.

- Are expected to have an extravaganza of EM counterparts (but signatures?).

**Joint GW-EM observations provide a number of benefits:**

- Accretion physics
- Cosmography

**LISA + Athena and/or LSST/Rubin** might observe up to tens MBHBs in both GW and EM.

**PTA sources** are massive and nearby, they might be ‘easily’ identified in the EM window.