Jets and electromagnetic outflows in binary mergers of compact objects

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Compact Objects as Astrophysical and Gravitational Probes
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GWs from a binary coalescence

- Einstein Equations (EE)
  \[ R_{ab} - g_{ab}R/2 = 8\pi G T_{ab} \]

- Linearized EE
  \[ g_{ab} = \eta_{ab} + h_{ab} \]
  \[ \Box \hat{h}_{ab} = -16\pi G T_{ab} \]
  - isolated sources at a far distance \( R \), and moving slowly
  \[ \hat{h}_{ij} = \left(2G/3R\right) \partial_{tt}^2 q_{ij} \]
  \[ \frac{dE}{dt} \sim (\partial_t h_{ij})^2 \]
  - energy losses in GW
  \[ L \sim M^2 r^4 \Omega^6 \sim (M/r)^5 \]
  will drive the binary to inspiral and eventually merge.

Post-Newtonian Theory
Numerical Simulations
Perturbation Theory

Gravity waves emitted as two neutron stars orbit one another
Detectors of GW on the ground

- Detectors of the strong GWs produced during the coalescence of massive binary compact objects, by measuring changes in the relative distances between perpendicular arms

$$|h| \sim \frac{\Delta L}{L}$$

Sensitive band $M \sim 1-100 \ M$
Detectors of GW in the space (I)

- eLISA: satellites following the earth around the Sun and measuring distance by interferometry between two arms. Continued by the ESA and expected to be launch at 2034 (but PATHFINDER will be launched this year!).

Sensitive band $M \sim 10^4 - 10^7 \, M_\odot$

[Amaro-Seoane et al, 2012]
Detectors of GW in the space (II)

• **Pulsar Timing Array**: GW affects the propagation of radio signal from pulsars to the Earth. IPTA collects data from an array of millisecond pulsars in $10^{-9}$-$10^{-6}$Hz.
  - Distinguish individual source and possible EM counterparts for $z \leq 1.5$ (Tanaka, Menou, Haiman 2011)
  - Improve sensitivity with future FAST and SKA

Sensitive to $10^8$-$10^{10} M_\odot$
Multi-messenger astronomy

- Correlate information from different channels; electromagnetic waves, gravitational waves and (possibly) neutrinos

Gravitational waves
- Tell us about large masses
- Travel directly to us
- Easy to determine distance
- Hard to determine sky location
- Impossible to measure redshift

EM waves
- Tell us about particles
- Often modified in transit
- Hard to determine distance
- Easy to determine sky location
- Easy to measure redshift
GW + EM counterparts

- GWs would allow to study GR in the strong field regime (alternative theories of gravity, population studies, test models of galaxy mergers, formation channels, determine the EoS at high densities ↔ nuclear interactions...)

- EM counterpart would allow to extract more information from the system (progenitor, environment) and the physical processes involved (plasma physics, accretion,...)

- Standard sirens (Schutz 1986, Holz&Hughes 2005) - analogous to the standard candles SNe
  GW luminosity distance~1-10% (limited by gravitational lensing)
  EM counterpart to localize the source in the sky and redshift study the distribution of the dark energy
EM outflows from strong GW events emitted by compact binary systems

Binary Black Holes: eLISA, PTA

Binary Neutron Stars: Advanced LIGO-VIRGO
Supermassive Binary Black Holes
eLISA, PTA
Supermassive black hole mergers

- Observations indicate the presence of supermassive BHs in the center of galaxies (Kormendy & Richstone 95), surrounded by gas and an accretion disk.

- In the Active Galactic Nuclei (AGN), the BHs are surrounded by a disc of matter likely magnetized.

- Galaxies have undergone some merger during their lifetimes.

- Galaxy mergers involve a very large range of scales, going from galaxy merger $\sim 10^2 \,(M/10^6 M_\odot) \, \text{kpc}$ to binary BH dynamics dominated by GW emission $\sim 10^{-3} \,(M/10^6 M_\odot) \, \text{pc}$.
The gas surrounding the binary BHs

- The stellar and gaseous environment extracts the angular momentum from the binary until gravitational radiation becomes important and induces the coalescence (Begelman et al. 80, Roos 81, Merrit & Milosavljevic 95)

- Depending on the balance between heating and cooling mechanism in the accretion disk (Bogdanovic et al 2009)
  - radiative inefficient accretion flows (RIAF) → hot gas cloud
  - efficient cooling → circumbinary disk
The circumbinary disk

• If the gas is not too tenuous the ions and electrons are thermally coupled $\rightarrow$ gas can cool efficiently through the electrons

• Gas settles into a geometrically thin/slim circumbinary disk, rotationally supported radially, and pressure supported vertically in the central part

• The gravitational binary torques can evacuate most of the gas near the binary, producing a hollowed region with a surface density much smaller than in the disk (Armitage & Natarajan 2002; Milosavljevic & Phinney 2005; MacFadyen & Milosavljevic 2008; Cuadra ++ 2009)
Circumbinary disk dynamics

- For $r \leq a$ the gas accretes into the BH, creating a hollowed region. The disk is truncated at the radius (inner edge) where gravitational binary torques $\sim$ disk viscous stresses (Milosavljevic & Phinney 2005 and references therein)

\[ t_{GW} = \frac{5 c^5 a^4}{64 G^3 M^3} \frac{(1+q)^2}{q} \sim a^4 \]
\[ t_{visc} = \frac{2 r^2}{3 \nu(r)} \sim r^2 \]

- early inspiral $t_{GW} \gg t_{visc}$ $\rightarrow$ disk's edge follows the binary with $r_{edge} \sim$ few $a$

- decoupling time $t_{GW} \sim t_{visc}$

- late inspiral $t_{GW} \ll t_{visc}$ $\rightarrow$ disk radius frozen
Circumbinary disk (early inspiral, $B \neq 0$)

- Circular orbits Newtonian MHD for a thin disk (Shi ++ 2011)
  - angular momentum transport driven consistently by MHD turbulence (MRI), larger than previously assumed $\alpha=O(0.1)$
  - MHD stresses introduces more matter in the gap
  - eccentric inner disk
  - $m=1$ mode (lump)
  - pair of gas streams until the formation of the lump (then only one stream)
Circumbinary disk (decoupling, $B \neq 0$)

- Inspiral during the decoupling phase, 2.5PN for the spacetime and relativistic MHD with radiation to sustain a “thin” disk ($H/R \sim 0.1$) via "consistent" cooling (Noble ++ 2012)
  - 100 orbits: long relaxation of the disk, then the spacetime is evolved, so the separation decreases from $a=20M$ to 8M
  - similar features to the Newtonian simulation during early inspiral
  - decrease of the accretion
  - BHs excised from the domain!!

\[
a_{\text{dec}} = 70 \left( \frac{d \ln \Sigma}{d \ln r} \right)^{-2/5} \left( \frac{H/r}{0.15} \right)^{-4/5} \left( \frac{\alpha}{0.01} \right)^{-4/5}
\]

\[
a_{\text{dec}} \sim 11 \left( \frac{d \ln \Sigma}{d \ln r/6} \right)^{-2/5} \left( \frac{H/r}{0.15} \right)^{-4/5} \left( \frac{\alpha}{0.7} \right)^{-4/5}
\]

\[
t_{\text{gr}} = \frac{5}{64} \left( \frac{a}{M} \right)^4 \frac{(1+q)^2}{q} M \ll t_{\text{in}} = a^{-1} (H/r)^{-2} (d \ln \Sigma/d \ln r)^{-1} \Omega^{-1} = a^{-1} (H/r)^{-2} (d \ln \Sigma/d \ln r)^{-1} (r/r_g)^{3/2} M,
\]
Circumbinary disk (coalescence, B≠0)

- Inspiral during the decoupling phase with full relativistic spacetime and MHD with radiation for the slim/thick disk (H/R~0.3) via "consistent" cooling (Farris ++ 2012, Gold ++ 2013)
  - the separation decreases from a~10M to merger
  - accretion through two spiral arms
  - increase the disk's eccentricity with the mass ratio
  - material pile-up at the inner edge when there is cooling
Zooming in on the black holes

- Near the BHs the density in the cavity is so low that even moderate magnetic fields may dominate the fluid dynamics
  
  \[ \nabla_a T^{ab}_{(\text{fluid})} \ll \nabla_a T^{ab}_{(\text{EM})} \rightarrow \mathbf{F}^{ab} \mathbf{J}_a \approx 0 \]

\[ \rightarrow \text{ force-free environment influenced by BH dynamics} \]

- General Relativity for the evolution of the spacetime
- Force-free to describe the magnetically dominated plasma

Maxwell equations

\[ \mathbf{F}^{ab} \mathbf{J}_b = 0 \]

- sub-domain with the BHs, excluding the disk
EM energy extraction from a single BH

- Rotational energy of the BH can be extracted through the magnetic field lines (Blandford & Znajek, MNRAS 1977)

- McKinney talk this morning!!

\[ \frac{dE}{dt} \sim B^2 a^2 \]

\[ a = \frac{J}{M^2} \ll 1 \]

- **membrane paradigm** (Thorne, Price, MacDonald 1986) endows a charge density to the horizon
Circumbinary disk (coalescence, force-free)

- A force-free environment can also extract the translational kinetic energy of the BH (CP++ 2010, Neilsen & CP++ 2011, Moesta & CP++ 2012)

\[ \frac{dE}{dt} \sim B^2 \left( \frac{v}{c} \right)^2 \]

- dual jet structure during inspiral, join into a single jet after merge
- diffuse quadrupolar luminosity
Circumbinary disk (coalescence, B≠0)

- Inspiral during the decoupling phase with full relativistic spacetime and MHD with radiation for the thick disk (H/R~0.3) via "consistent" cooling (Farris ++ 2012, Gold ++ 2013, Gold ++ 2014)
- separation decreases from a~10M to merger
- accretion through two spiral arms
- increase the disk's eccentricity & mass ratio
- material pile-up at the inner edge (w cooling)
- dual jet structure!!
The hot gas cloud

- If the gas is sufficiently tenuous $\leq 10^{-11}\text{g/cm}^3$ there will be a two-temperature flow that will radiate heat inefficiently.

- The energy produced by accretion and turbulent stresses is stored as heat, so that the gas thermal pressure is comparable to its gravitational potential energy (Ichimaru 1977; Rees et al 1982; Narayan and Yi 1994).

- Geometrically thick gas cloud with inflow velocities comparable to sound and Keplerian velocity.
- Binary torques incapable to evacuate the central region.
- Gas cloud up to the merger.
Gas cloud: dynamics near merger

- Unmagnetized gas cloud accretion on a binary BH system (Bode ++ 2010, Farris ++ 2010, Bode ++ 2011)

- Strong shock produce a pair of denser wakes behind the orbiting holes and a denser central region

- Generic feature: gradual rise and sudden drop-off in luminosity regardless of the spin orientation and mass ratios
Gas cloud: dynamics with magnetic fields

- Gas cloud with magnetic field, general relativistic MHD (Giacomazzo ++ 2012)
  - start with constant magnetic field that grows up to $\beta \sim 1$
  - extended outflow with increasing luminosity during the inspiral, with a drop-off after merger
Summary (I)

- Magnetic fields play a crucial role, even if initially small
  - outflow in magnetized gas cloud \(\rightarrow\) thick torus
  - enlarged viscosity due to MRI in thin/slim disks
  - dual jet structure near the black holes

- Still a lot to do: PN theory\(^*\) + full GR, radiation, slim/thin/thick disks?, higher magnetizations...
Binary Neutron Stars

Advanced LIGO
Binary Neutron Stars

- NS are compact objects of $R \sim 10$ km and $M \sim 1-2 M_\odot$ presenting strong magnetic fields ranging from $B \sim 10^8-10^{12} G$

- Main target for LIGO: GW will tell us their masses, constraint their radius $\rightarrow$ equation of state

- Binary NS mergers will form a BH surrounded by a massive accretion disk: expected to produce short Gamma Ray Burst.
EM/GW precursors of a short GBRs

- Binary NS
- HMNS
- BH + disk

Interaction of the NS’s magnetospheres (Hansen & Lyutikov, MNRAS 2001)
Isolated NS magnetospheres

- A strong magnetic field combined with rotation produces an electric force that pulls electrons from the surface and populates the magnetosphere (Goldreich & Julian, Ap. J. 1969)

- Numerical solution of the EM radiation by the force-free magnetosphere of an aligned and oblique rotator (Spitkovsky 2007)

\[ L_{\text{pulsar}} = k_1 \frac{\mu^2 \Omega^4_*}{c^3} (1 + k_2 \sin^2 \alpha), \]
Modeling binary NS magnetospheres

- Different approaches to model the EM luminosity of binary NS system
  - theoretical estimates based on:
    I) unipolar inductor
    II) DC circuit model
  - numerical approach: difficult to solve simultaneously the star and its magnetosphere
    I) ideal MHD neglecting matter contributions
      + force-free condition (McKinney & Gammie, APJ. 2004, Paschalidis ++ 2013)
    II) match two separate set of solutions (Lehner, CP ++ PRD 2012)
Theoretical estimates for binary NS

- **Unipolar inductor**: conductor (star) moving in the external magnetic field produced by the other star (Goldreich & Lynden Bell 1969, Hansen & Lyutikov 2001)

\[
L_{\text{orb}} \approx 4\pi R^2 B_m^2 \left( \frac{R}{a} \right)^6 \frac{v^2}{c}
\approx 7.4 \times 10^{45} \text{ergs s}^{-1} \left( \frac{B_m}{10^{15} \text{G}} \right)^2 \left( \frac{a}{10^7 \text{cm}} \right)^{-7}
\]

- **Circuit model** (Piro 2012, Lai 2012)

\[
\dot{E}_{\text{diss}} = \left( \frac{v_{\text{rel}}}{c} \right)^2 \frac{B_*^2 R_*^6 R_c^2 c}{\pi a^6} \frac{\omega a}{\pi a^6}
= 1.7 \times 10^{44} \left( \frac{B_*}{10^{13} \text{G}} \right)^2 \left( \frac{a}{30 \text{ km}} \right)^{-7} \text{erg/s}
\]
Numerical solution for isolated NS

- Rotating stable NS with an initial dipolar field
- Evolve the **resistive MHD** with ideal/force-free inside/outside the star until the system relaxes to a stationary solution (CP, MNRAS 2013)

\[
J^i = q[(1-H)\nu_d^i + H\nu_d^i] + \frac{\sigma}{1+\zeta^2} \left[ \varepsilon^i + \frac{\gamma^2}{B^2} \left\{ (E^kB_k)B^i + \chi(E^2-B^2)E^i \right\} \right]
\]

\[
H(\rho, \rho_o) = \frac{2}{1+\epsilon^2K(\rho-\rho_o)}
\]
Numerical solution for binary NS

- the magnetospheres will co-rotate and produce a shear layer between the stars (CP ++ 2013)
Numerical solution of binary NS (II)

- Current sheets and dissipation regions like in pulsars, with an emitted power depending on the topology of the fields.
- Significant EM radiation during the inspiral due to the interaction of the magnetospheres $\sim10^{40}-10^{42}$ ergs/s with a softer dependence on $\Omega$

- Luminosity depends on the orientation of the magnetic dipolar moments (Ponce, CP ++ 2014), on its magnitude and on the spin of the stars (CP ++ 2015)
**Observability prospects of binary NS**

* Strong/dynamic magnetic field produces dense and hot (optically thick) pair plasma

- Bubble-Driven Shocks during the inspiral: *synchrotron radiation* from the shock (Medvedev 2012)
- Explosion model near the merger: *thermal spectrum* (Paczynski, APJ Letters 1986)

* Moderate magnetic fields: *non-thermal spectrum* with features similars to (mili-second) pulsars
Luminosity of a BH+NS

- Theoretical estimates
  (Hansen & Lyutikov 2000, McWilliams & Levin 2011)

\[
L = 2 \frac{V^2}{R_H} = \frac{8\epsilon}{\pi} (\alpha v)^2 B^2 M_{BH}^2
= 3 \times 10^{46} \epsilon \left( \frac{\alpha v}{c} \right)^2 \left( \frac{B_0}{10^{12} \text{G}} \right)^2 \left( \frac{r_{NS}}{r} \right)^6 \left( \frac{M_{BH}}{10 M_\odot} \right)^2 \text{erg/s}
\]

- Numerical simulations
  (Paschalidis ++ 2013)

\[
L_{EM,MD} \approx 2.4 \times 10^{41} \left( \frac{v}{0.3c} \right)^2 \left( \frac{B_{NS,p}}{10^{13} \text{G}} \right)^2 \left( \frac{M_{NS}}{1.4 M_\odot} \right)^2 \left( \frac{r}{6.6 R_{NS}} \right)^{-6} \text{erg/s},
\]
Summary (II)

- Significant EM radiation during the inspiral due to the interaction of the magnetospheres
  - luminosity increases as the orbit shrinks $L \sim \Omega^{2.4}$
  - power emitted in EM waves depends on the dipolar magnetic fields and on the spin of the stars
  - EM spectrum might vary depending on the magnetic field strength and on the stage of the coalescence

Thank you for your attention!