Black Hole-Neutron Star and Neutron Star Binaries as Progenitors of sGRBs

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LIGO/Virgo GWs and EM Counterparts

- Events:
  - GW170817 + EM counterpart GRB 170817A: classified as a BNS
  - GW190425 + “GRB190425”: classified as a BNS
  - S190426c: 52% chance to be a BHNS, 13% to be BNS
  - S190923y: 67% chance to be a BHNS
  - ...... See A. Corsi’s talk for a summary
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Merging BHNSs and BNSs are the most popular candidate progenitors of sGRBs: Eichler et al. ’89, Narayan et al. ’92, Mochkovitch et al. ’93.

Our numerical results
Compact mergers: Magnetized BHNSs

Etienne et al, ’12
Magnetized BHNS Mergers I

Etienne et al, ’12: Following the BHNS merger, the B-field lines are wound into an almost purely toroidal configuration

\[
\text{BHNS: mas ratio } q = \frac{M_{BH}}{M_{NS}} = 3 \\
\chi_{BH} = 0.75
\]

Evolution: Illinois GRMHD code
See Etienne-Werneck’s talk

No jets
Beckwith et al. 08: BH + disk can launch a jet if the disk has a strong poloidal B-field component.

**Right conditions:** Pulsar-like B-field

**Problem:** Evolution of external B-field where $\rho_0 \approx 0$

**Solution:** External & variable atmosphere where exterior gas-to-magnetic-pressure ratio is $\beta_0 = \text{const.} \ll 1$

Magnetic-pressure dominance, but not magnetic-energy density dominance.

Paschalidis, MR, Shapiro, ‘14
BHNS as Progenitors of sGRBs

- Disk lifetime: \[ \Delta t \sim \frac{M_{\text{disk}}}{\dot{M}} \sim 0.1 \, \text{s} \]
  consistent with sGRB T90

- Max. magnetization in the outflow:
  \[ \sim \frac{b^2}{2 \rho_0} = \frac{B^2}{8 \pi \rho_0} \sim 100 \]
  Vlahakis et al, ’03: Terminal \( \Gamma \) in the jet equals \( b^2/2\rho_0 \)

- Poynting Luminosity:
  \[ L_{EM} = 10^{51} \, \text{erg/s} \]
  Consistent with Blandford-Znajek mechanism
  \[ L_{EM} \sim 10^{51} (a/m)^2 (m/5.6M_\odot)^2 (B/10^{15} \, G)^2 \, \text{erg/s} \]
BHNS as Progenitors of sGRBs

Population synthesis studies: most likely mass-ratio \( q = \frac{M_{BH}}{M_{NS}} \) is \( \approx 7 \)

NS disruption requires \( \chi_{BH} \approx 0.2 \text{–} 0.7 \)

LIGO/Virgo BBH detections: high mass-ratio and/or low-spin

Strong constraint!

Unlikely to observe sGRBs from BHNS

Foucart ‘20
BHNS as Progenitors of sGRBs

What about other EM counterparts?

BHNS with a spinning NS: More ejecta

May lead to an observable kilonova

MR et al. (in prep.)
Compact mergers: Magnetized BNSs

MR et al. ’16
At least three possible scenarios:

- **NSNS:** 
  - **Compact merger scenarios:**
  - **Supramassive remnant**
  - **Delayed collapse**
  - **Prompt collapse**

- **NSNS:**
  - **Stable**
  - **Hypermassive NS**
  - **Accretion**

Bartos et al. ‘12
BNS Scenario: Stable Remnant I

Assumption: Remnant of a BNS merger

- B-field collimation
- Outflow: $\Gamma = 1.01 - 1.03$
- Pulsar-like luminosity $\sim 10^{43}$ erg/s

Inconsistent with sGRBs
BNS Scenario: Stable Remnant II

- B-field collimation
- Outflow $\Gamma \lesssim 1.05$

Inconsistent with sGRBs

Möstä et al. ’20: magnetized
Long-lived HMNS
+ neutrinos
See Radice’s talk

Less baryon pollution then terminal $\Gamma \approx 5$
MR et al. ’16-19

Max. magnetization in the outflow: consistent with sGRB T90

Disk lifetime: \( \Delta t \sim \frac{M_{\text{disk}}}{\dot{M}} \sim 0.1 \text{ s} \)

consistent with sGRB T90

Max. magnetization in the outflow:

\[ \sim \frac{b^2}{2 \rho_0} = \Gamma_{L(\text{asy})} \sim 100 \]

Simulations: \( L_{\text{EM}} \sim 10^{51.5 \pm 1} \text{ erg/s} \)

BNS Scenario: Delayed Collapse

\( t/M = 4606 \)

\( L_{\text{EM}} \sim 10^{51} \text{ erg s}^{-1} \)

Dier is lifetime:

\( \Delta t \sim \frac{M_{\text{disk}}}{\dot{M}} \sim 0.1 \text{ s} \)

consistent with sGRB T90

Max. magnetization in the outflow:

\[ \sim \frac{b^2}{2 \rho_0} = \Gamma_{L(\text{asy})} \sim 100 \]

Simulations: \( L_{\text{EM}} \sim 10^{51.5 \pm 1} \text{ erg/s} \)
BNS Scenario: Prompt Collapse

- No B-field collimation
- No outflow
- Really small accretion disk

EM counterpart before merger: see e.g. Lehner et al. ’12
Progenitors of fast radio bursts: see e.g. Totani ’13, ...
GW170817, GRMHD and the NS maximum mass

\[ M_{\text{max}}^{\text{sph}} \leq M \leq M_{\text{max}}^{\text{sup}} \]

Supramasive

\[ M_{\text{max}}^{\text{sup}} \leq M \leq M_{\text{thr}} \]

Delayed collapse
Consistent with sGRBs

Prompt collapse

\[ M_{\text{thr}} \leq M \]

Using Hartle’s causal argument:

\[ \beta M_{\text{max}}^{\text{sph}} \approx M_{\text{max}}^{\text{sup}} \lesssim 2.74 \lesssim M_{\text{thr}} \approx \alpha M_{\text{max}}^{\text{sph}}. \]

Typically

\[ \beta \approx 1.2 \quad \Rightarrow \quad M_{\text{max}}^{\text{sph}} \lesssim 2.28 \]

Using Hartle’s causal argument:

\[ \beta \approx 1.27 \quad \Rightarrow \quad M_{\text{max}}^{\text{sph}} \lesssim 2.16 \]

Consistent with Margali et al., Rezzolla et al., Shibata et al.
**Ergostars**

Ergoregions are associated with two astrophysical processes which are both related to the extraction of energy from a spinning BH:

- Penrose process
- Powering of relativistic jets through the Blandford-Znajek process

**key ingredient:**
BH Horizon

**Membrane paradigm:**
Energy and angular momentum are extracted along B-field lines threading from the horizon
Ergostars

**Ergoregions** are associated with two astrophysical processes which are both related to the extraction of energy from a spinning BH:

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**Membrane paradigm:**
Energy and angular momentum are extracted along B-field lines threading from the horizon

**Komissarov ’04–’05:**
Energy and angular momentum are extracted along B-field lines threading the ergoregion

Preliminary results using Force-Free evolutions + Cowling approx. seem to confirm this claim: MR et al. ’12
Ergostars: Dinamically Unstable

Differentially rotating $\Gamma = 3$ polytropes:

Komatsu et al. ‘89
Following Hartle, we took the ALF2 EOS and replace $\rho_0 > \rho_{0s}$ with a compressible EOS

$$P = (\rho - \rho_s) + P_s$$

maximum possible stiffness

Here, we take $\rho_{0s} = 2.7 \times 10^{14} \text{ gr/cm}^3$
Ergostars: Dinamically Stable

Differentially rotating NS with the ALF2cc EOS

Tsokaros, MR et al. ’20
Assumption: Ergostars are BNS remnants

Max. magnetization in the outflow:
\[ M = 8 \times 10^{-2} \]
\[
\dot{M}_{\text{NS}} \sim 10^{89} \text{ as functions of retarded time extracted at } M_{\text{L}} \), which
\[
45 \times (1 - M_{\text{q}}) \frac{c}{v_{\text{tid}}} \text{ (see also } M_{\text{BH}}^{2} \text{). As the basic ingredient for jet launching}
\[
\tilde{\rho} \sim 10^{-1} \text{.}
\]

Firstly, the less magnetic energy left to launch a jet. The
\[ \frac{\dot{M}}{M_{\text{q}}} \text{, therefore the smaller the mass of the remnant disk and, conse-}
\]
\[ \text{M} \text{ decreases as the mass ratio of the binary increases. The closer}
\[ \text{the BH poles.}
\]
\[ \text{that ties fluid elements in the disk to low density debris above}
\]
\[ \text{the BHNS simulation the magnetic field strength above the BH poles is}
\]
\[ \text{2 during the plunge phase. We do not find evidence of mag-}
\]
\[ \text{As the frozen-in magnetic field has been dragged into the BH}
\]
\[ \text{Note that we normalized the mass of the BH to}
\]
\[ \text{It is therefore likely that the BZ mechanism is operating in}
\]
\[ \text{is consistent with that generated by the BZ mechanism [12].}
\]
\[ \text{resolution. On the other hand, the outgoing Poynting luminos-}
\]
\[ \text{Neutrino effects are ignored}
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Blandford-Znajek effect
\[ L_{\text{jet}} \sim 10^{51.2} - 10^{51.6} \]

Neutrino effects are ignored

\[ \text{In the above section, we described the effects of the BH}
\]
\[ \text{ISCO is}
\]
\[ \text{So, the critical spin at which tidal disruption occurs at the}
\]
\[ \text{formation channels may arise in BHNS [13]. The most likely BHNS mass ratio may be}
\]
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Conclusions

We are in a golden era where we can test our theory/models against observations and numerical simulations. We can do now:

- **Multimessenger astronomy**
- Discover new physical effects,
- Use simulations to constraints EoSs,
- Constraint theory beyond GR

Computational astrophysics allows to explain some of the LIGO/Virgo GW detections. However, more detailed microphysics + magnetic field are both needed.