Impact of Neutrinos in Neutron-Star Mergers

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With: A. Bauswein, J. Guilet, R. Ardevol, M. Obergauliner, H.-Th. Janka, S. Goriely, and others
Movie: NS-NS Merger
(SPH simulation, by A. Bauswein)
Movie: NS-BH Merger
(SPH simulation, by R. Ardevol, A. Bauswein)
Ejecta Components, Modeling Status

**dynamical/prompt ejecta**
→ tidal tails
→ shock-heated

**3D, GR, ν-transport, MHD**
(Rosswog & Korobkin, Bauswein & Janka, Sekiguchi & Shibata, Hotokezaka, Rezzolla, Radice, Kiuchi, Foucart, Duez, ...)

**post-merger ejecta**
→ neutrino-driven
→ viscous/MHD driven expansion
→ MHD turbulence

**ν-tran, MHD/Vis, 3D, GR**
(Fernandez & Metzger, Perego & Martin, Siegel, Kiuchi, Ru, Fujibayashi...)

**NS-BH, NS-NS, NS/BH**

**Black Hole – Torus System**

**Inspiral**

**Merger**

**Post-Merger Remnant**

**(Hyper-) Massive Neutron Star**
Typical outflow properties:

- outflow masses: $M \sim 0.001 - 0.1 \text{ Msun}$
- electron fraction: $Y_e < 0.1$ (*)
- entropy per baryon: $s \sim 1 - 30 \text{ kB}$
- velocity: $v \sim 0.2 - 0.4 \text{ c}$

(*: Depends on neutrino treatment for NS-NS mergers)
**Prompt/Dynamical Ejecta**

(as obtained in OJ, Bauswein, Ardevol, Goriely, Janka ’15)

**NS-NS**

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- outflow masses: $M \sim 0.001 – 0.1 \text{ Msun}$
- electron fraction: $Ye < 0.1$ (*)
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**NS-BH**

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- electron fraction: $Ye < 0.1$ (*)
- entropy per baryon: $s \sim 1 – 30 \text{ kB}$
- velocity: $v \sim 0.2 – 0.4 \text{ c}$

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**softer EOS yields...**

- **larger** torus masses (in case of collapse)
- **larger** outflow masses
- **larger** outflow velocities

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**softer EOS yields...**

- **smaller** torus masses (in case of collapse)
- **smaller** outflow masses

( * : Depends on neutrino treatment for NS-NS mergers)
Typical nucleosynthesis pattern:

- sub-solar for $A < 140$ (*)
- solar-like for $A > 140$

Typical outflow properties:

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(* : Depends on neutrino treatment for NS-NS mergers)
...can be quite significant. Dynamical ejecta may also produce lighter elements

more simulations with accurate neutrino transport needed
Post-Merger BH-Torus
(directly after its formation)

Role of neutrinos:
- cool torus and impact the accretion rate!
- determine/alter Ye in outflows!
- possibly launch/contribute to GRB jet!

\[ n + \nu_e \rightarrow p + e^- \]
\[ p + \bar{\nu}_e \rightarrow n + e^+ \]
\[ n + e^+ \rightarrow p + \bar{\nu}_e \]
“ALCAR” Neutrino Transport Module

Radiation-hydro with Boltzmann solver too expensive!

Our approach:

➔ Energy-dependent two-moment scheme with local closure (*M1 scheme*)

\[
\begin{align*}
E &= \int d\Omega I(x, n, \epsilon, t) \\
F^i &= \int d\Omega I(x, n, \epsilon, t) n^i \\
P^{ij} &= \int d\Omega I(x, n, c, t) n^i n^j \\
Q^{ijk} &= \int d\Omega I(x, n, c, t) n^i n^j n^k
\end{align*}
\]

\[\begin{aligned}
\partial_t E + \nabla_j F^j + \nabla_j (v^j E) + (\nabla_j v^k) P^{jk} - (\nabla_j v^k) \partial_\epsilon (\epsilon P^{jk}) &= C^{(1)} \\
\partial_t F^i + c^2 \nabla_j P^{ij} + \nabla_j (v^j F^i) + F^i \nabla_j v^i - (\nabla_j v_k) \partial_\epsilon (\epsilon Q^{ijk}) &= C^{(1),i}
\end{aligned}\]

\[
\begin{align*}
P^{ij} &= P^{ij}(E, F^i) \\
Q^{ijk} &= Q^{ijk}(E, F^i)
\end{align*}
\]

\{ approximate algebraic closure relations (e.g. “Minerbo closure”) \}

Saves two degrees of freedom of nu-phase space!

BUT: Limited accuracy in optically thin regions

Comparison Between M1 and Ray Tracing

(a) $\nu_e$ energy density

(b) $\nu_e$ energy density

(c) rel. difference $\nu_e$ energy density

(d) $\nu_e$ energy density

(e) $\nu_e$ energy density

(f) rel. difference: $\nu_e$ flux density

(g) $\nu_e$ heating/cooling rates

(h) $\nu_e$ heating/cooling rates

(i) $\nu_e$ capture equil. electron fraction

(j) $\nu_e$ capture equil. electron fraction

[Diagrams showing energy densities, flux densities, heating/cooling rates, and electron fractions for M1 and Ray Tracing schemes.]
Typical ejecta properties:

- outflow masses: ~ 5-20% of torus mass
- electron fraction: Ye ~ 0.1-0.3
- entropy per baryon: s ~ 10 – 30 kB
- velocity: v ~ 0.05– 0.1 c

- **small** neutrino-driven component
- **dominant** viscous component
Disk Properties

2 main evolutionary phases:
➔ first few 100 ms: "Neutrino-dominated accretion flow" (NDAF)
➔ neutrino cooling balances viscous heating
➔ ejecta (mainly) driven by neutrino-heating
➔ Ye in ejecta determined by neutrino captures
Disk Properties

2 main evolutionary phases:

- subsequently: "Advection-dominated accretion flow" (ADAF)
- viscous heating dominates neutrino cooling

- ejecta (mainly) driven by viscous effects
- Ye in ejecta determined by electron/positron captures

\[ \bar{p} + e^- \rightarrow n + \bar{\nu}_e \]
\[ n + e^+ \rightarrow p + \bar{\nu}_e \]

\[ Y_e \rightarrow Y_e^\beta = Y_e(\rho, T, \mu_\nu = 0) \]
Combined nucleosynthesis yields

- DISK ejecta (mainly $A \sim 90 - 140$)
- PROMPT ejecta (mainly $A \sim 140 - 210$)
- DISK + PROMPT ejecta

- nicely recovers the full mass range $A > 90$
- BH-torus ejecta could be significant source of intermediate mass elements with $90 < A < 140$
Magnetic fields?

- ...are essential for angular momentum transport and MHD-driven Jet

- **Major challenges:**
  - need 3D because of anti-dynamo theorem
  - need high resolution to resolve relevant scales

(see talks by Siegel and Tchekovskoy)

- 2D M1-MHD simulations (not sufficient to obtain long-term ejecta):
Can the Magnetorotational instability grow in remnants of NS-mergers?

- In NS remnants: slowed down by neutrino-viscosity and -drag
- In BH-torus remnants: ideal growth

Neutrino viscosity (on length scales longer than neutrino mean free path):

\[
\nu = 1.2 \times 10^{10} \left( \frac{T}{10 \text{ MeV}} \right)^2 \left( \frac{\rho}{10^{13} \text{ g cm}^{-3}} \right)^{-2} \text{ cm}^2 \text{ s}^{-1}, \quad (2)
\]

Neutrino drag damping rate (on length scales shorter than neutrino mean free path):

\[
\Gamma = 6 \times 10^3 \left( \frac{T}{10 \text{ MeV}} \right)^6 \text{ s}^{-1}.
\]
Gamma-Ray Bursts

- first detected 1967 by VELA satellites
- since then ~ few 100 suggested possibilities for central engines
- since BATSE: must be of cosmological origin
- source is moving highly relativistically
- natural suggestion: jet from rotating compact object
- long bursts (T>2s): connection to death of massive stars
- short bursts (T<2s) still mysterious, most likely from NS mergers

(NASA)
Popular central engine scenarios

➔ neutrino-pair annihilation
- neutrinos tap gravitational energy of disk
  e+-e- pairs thermalize → thermal fireball
- efficiency of converting gravitational energy into jet energy?
- baryon loading in the funnel?

➔ Blandford-Znajek process
- B-field taps rotation energy of central BH
  → Poynting-dominated jet
- efficient only for large-scale poloidal B-fields
- can large-scale fields be produced and sustained? MRI? Dynamo?

➔ magnetar spin-down emission
- B-field taps rotation energy of central NS
  → Poynting dominated jet
- is dipole model applicable?
- consistent with short burst timescale?

(Hirose+ '04)
(Metzger+ '11)
EM Counterparts: Short Gamma-Ray Bursts

- Suggested models:
  - Neutrino pair annihilation
  - Blandford-Znajek process
  - Magnetar dipole emission

*Necessary conditions for the jet to explain sGRB:*

- Total energy: $E \sim 10^{48} - 10^{50}$ erg
- Lorentz factor: $\Gamma \sim 10 - 100$

*Tested using for the first time time-dependent neutrino-hydrodynamics simulations*

Geometry of Dynamical Ejecta

NS-NS

Bauswein et. al. '13

NS-BH

Just et. al. '15

Hotokezaka et. al. '13

(Hotokezaka et. al. '13)
Symmetric NS-NS Merger

- baryon loading in the funnel too high, no jet launched
Asymmetric NS-NS Merger

- jet is **successfully launched**, but then **dissipates most of its kinetic energy** into cloud of dynamical ejecta
NS-BH Merger

- no dynamical ejecta in polar regions → jet can expand freely
- however, energy too low to explain majority of sGRBs
Summary

- Neutrinos can have strong impact on Ye, ejecta mass, remnant cooling, MRI, and jet.
- R-process nucleosynthesis:
  - For neutrino-driven winds (from HMNS or disk): energy-dependent neutrino transport inevitable.
  - For viscous-like winds: maybe no transport needed, leakage sufficient.
  - For dynamical ejecta from NS-NS: e-dependent nu-transport desirable.
  - For dynamical ejecta from NS-BH: nu-transport probably negligible.
- Jets:
  - Neutrino annihilation probably not the main agent, but could help clearing the funnel.
  - For accurate annihilation rate: e-dependent nu-transport desirable.
- MRI in the remnant:
  - Slowed down by neutrinos in the HMNS.
- Still major challenge to combine nu-transport with GR and MHD but major steps have been taken by various groups.
It could be worse…

→ … in (2D) core-collapse supernovae small modifications in the nu-transport can decide if star explodes or not

(Just et al, in prep)