Neutron star merger ejecta estimation from kilonova light curve (surrogates)

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Neutron Star merger

Top-Down view
AK et al., PRD (2022); movies available on atulkedia93.github.io

Cross-section Edge-on view

DB: rho.xy.h5
Cycle: 0
Time: 0

Rest Mass Density [1/Msun^2]

DB: rho.xz.h5
Cycle: 0
Time: 0

Rest Mass Density [1/Msun^2]
Equation of state (EoS) $P(\rho, Y_e, T)$ in the form of Pressure v. density $P(\rho)$

Impact of the EoS on the remnant

Dietrich et al. GRG (2020)

AK et al., PRD (2022)
AT2017gfo / GW170817


Abbott et al. PRL 2017, LIGO+Virgo

sGRB ~ 2s
Multi-Messenger Astrophysics

**Binary properties**

\( \mathbf{x} = \{ M_{\text{BH}}, M_{\text{NS}}, \chi_{\text{BH}}, \Lambda_{\text{NS}}, \ldots \} \)

**Outflow properties**

\( \mathbf{y} = \{ M_{\text{dyn}}, M_{\text{wind}}, v_{\text{dyn}}, v_{\text{wind}}, \ldots \} \)

**Light curves**

\( \mathbf{y}_{\mathbf{1}} \rightarrow \mathbf{y}_{\mathbf{11}}, \mathbf{y}_{\mathbf{12}}, \mathbf{y}_{\mathbf{13}}, \ldots \)

\( \mathbf{y}_{\mathbf{2}} \rightarrow \mathbf{y}_{\ldots} \)

Fit formulae to numerical simulations

Radiative transfer simulations

Ejecta components corresponding to the kilonova spectrum

Kasen et al. Nature 2017
EM v GW ejecta parameter tension

Assuming (Torus, Peanut morphology)

Ejecta masses (Kilonova approach) > Ejecta masses (GW approach)
EM v GW ejecta parameter tension

Kilonova approach ➞ Assuming (Torus, Peanut morphology)

GW approach

Ejecta masses (Kilonova approach) > Ejecta masses (GW approach)
Ejecta profiles

TABLE I. Ejecta morphologies and compositions studied in this paper. The composition of the dynamical component is fixed at $Y_e = 0.04$. In terms of this notation, the previous investigation studied a TPwind2 outflow [32].

<table>
<thead>
<tr>
<th>Wind</th>
<th>Name</th>
<th>Morphology</th>
<th>$Y_e$</th>
<th>Dynamical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TPwind1</td>
<td>Peanut</td>
<td>0.37</td>
<td>Torus</td>
</tr>
<tr>
<td></td>
<td>TSwind1</td>
<td>Spherical</td>
<td>0.37</td>
<td>Torus</td>
</tr>
<tr>
<td></td>
<td>TSwind2</td>
<td>Spherical</td>
<td>0.27</td>
<td>Torus</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass [Mo]</th>
<th>Velocity [c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001, 0.003, 0.01, 0.03, 0.1</td>
<td>0.05, 0.15, 0.3</td>
</tr>
</tbody>
</table>

Korobkin et al 2021 ; Wollaeger et al 2021

225 + 225 (active learning sims) = 450 /$\{\text{Name}\}$
Gaussian Process regression Surrogate models

TPwind1 wavelength interpolation

TSwind2 light curve interpolation

Simulation data: [https://zenodo.org/record/7335963#.ZAE4iXbMKsM](https://zenodo.org/record/7335963#.ZAE4iXbMKsM)

GP Surrogate models: [https://github.com/markoris/surrogate_kne](https://github.com/markoris/surrogate_kne)
Simulation setup

- Radiative transfer software using tabulated binned opacities on SuperNu. (Wollaeger et al 2013, 2014)

- Composition and radioactive heating from r-process elements, nucleosynthetic results from WinNet. (Winteler et al. 2012)

- Nuclear model
  - Heating rates (Korobkin et al. 2012)
  - Thermalization model of (Barnes et al. (2016))
  - Atomic opacities (Fontes et at. 2020)

- Reprocessing of light from one component to another.

- Active learning (by reducing $\chi^2$ error) to expand the spanned parameter space.

Fit Light curves (to AT2017gfo)

TorusPeanut (high wind Ye)

TorusSpherical (low wind Ye)

AK et al
Phys. Rev. Research 5, 013168 (2023)
EM v GW ejecta parameter estimation

AK et al, Phys. Rev. Research 5, 013168 (2023)
EM v GW ejecta parameter estimation

Ejecta parameters with the broader ejecta model:

- Different morphologies predict different ranges in the parameter space
- TS\text{Wind2} and TP\text{wind2} are significantly closer to GW estimate!
- Some differences still remains!

Collaborators: Marko Ristic (also in this N3AS school), R. O’Shaughnessy (RIT), R. Wollaeger, C. Fontes, E. Chase, C. Fryer, O. Korobkin (LANL)

AK et al, Phys. Rev. Research 5, 013168 (2023)
Summary

• Upgrades to nuclear and atomic physics
• Upgrades to the binned opacity straight from MNRAS (Fontes et al (2022))
• Thermalization efficiencies (relativistic using AK et al PRE 2021)
• Heating rates new formulation (Rosswog and Korobkin 2022);
  Update example at Bulla, MNRAS (2023)

Ongoing work

• Multi-messenger ejecta inference
• GW and EM disagree in about ejecta properties
• New radiative transfer simulations with broader ejecta morphologies
• GW and EM still disagree, but less so.
  • Blue luminosity slightly underluminous
• More nuclear and atomic physics improvements are needed in the model

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