Radiation hydrodynamics modeling of kilonovae with SNEC

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ABSTRACT
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Key words: keyword1 – keyword2 – keyword3

(i) Use bibtex keys from INSPIRE. I have a script to generate the bibtex automatically from those
(ii) The section titles are just suggestions and will be finalized later
(iii) Let's start with assembling the relevant plots and some text for the methods section

1 INTRODUCTION

2 METHODS

- Brief overview of SNEC
- EOS
- Opacities

The average opacities for mixture of r-process elements are mainly determined by initial Y_e of the ejecta. Motivated by (Tanaka et al. (2018)), we design a simple formula for gray opacity κ as a function of initial Y_e. For simplicity, opacity does not change over time. It should be noted that multi-color light curves can not be well approximated by gray opacities.

$$\kappa = 1 + \frac{9}{1 + (4Y_e)^{12}} \mathrm{cm}^2 \mathrm{g}^{-1} \tag{1}$$

- Heating rates

At the times relevant for kilonovae, the ejecta has already lost all of its initial thermal energy at expansion, and the dominant source of heating is constituted by the decays of heavy elements produced in the r-process. This heating can be described by a specific heating rate which can be derived by evolving the system of the numerous characteristic nuclides in time while accounting for their mutual interactions.
Here, time-dependent heating rates obtained using the nuclear reaction network SkyNet with a FRDM nuclear mass model are employed. A single SkyNet run is determined by the set of thermodynamic variables initial electron fraction Y_e, initial specific entropy s and expansion timescale τ. The rates are thus computed on a comprehensive grid with $0.02 \le Y_e \le 0.48$ linearly spaced, $1.82\ \mathrm{k_B/baryon} \le s \le 100\ \mathrm{k_B/baryon}$ and $1.36\ \mathrm{ms} \le \tau \le 100\ \mathrm{ms}$ log-spaced, the results on a representative subgrid being reported in Figure 1.

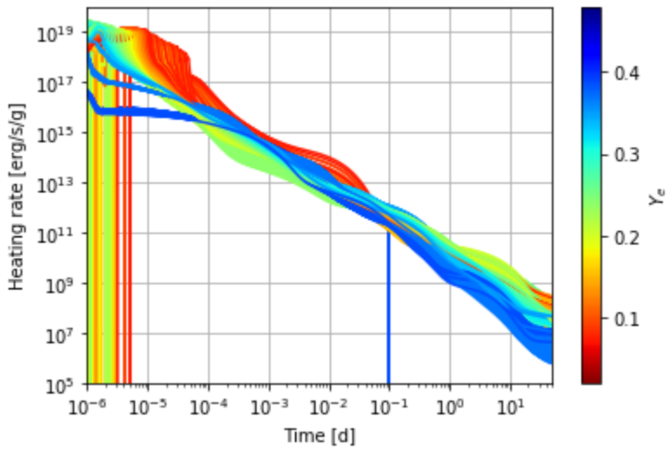

Figure 1. Heating rate trajectories as obtained by SkyNet on a subgrid of thermodynamic variables $0.05 \le Y_e \le 0.4$, $3\ \mathrm{k_B/baryon} \le s \le 50\ \mathrm{k_B/baryon}$ and $1\ \mathrm{ms} \le \tau \le 30$ ms for visual clarity. Trajectories are color-coded to indicate different initial electron fractions. Vertical lines correspond to SkyNet noise which is averaged out in the fit procedure.

In order to derive the heating rate for arbitrary initial conditions, the above trajectories are reduced to a parametrized functional form by means of a fit procedure intended to cover the time interval from 0.1 s to 50 days post-merger, and, in particular, a distinction between time regimes is introduced. For early times $t \lesssim 0.1$ days, the analytic fitting formula, derived from detailed nucleosynthesis calculations (Korobkin et al. (2012)), is employed:

$$\dot{\epsilon}_r(t) = \epsilon_0 \epsilon_{th} \left(\frac{1}{2} - \frac{1}{\pi} \arctan \left[\frac{t - t_0}{\sigma} \right] \right)^{\alpha}, \tag{2}$$

where ϵ_0, α, t_0 and σ are considered fit parameters, while $\epsilon_{th} < 1$ is the thermalization efficiency. At late times $t \gtrsim 0.1$ days instead, we expect a power-law fit to be a sufficiently good approximation of the heating rates, and thus the fitting formula becomes:

$$\dot{\epsilon}_r(t) = \epsilon'_0 \epsilon_{th} t^{-\alpha'}, \tag{3}$$

with ϵ'_0 and α' additional fit parameters. The heating rate fits, as

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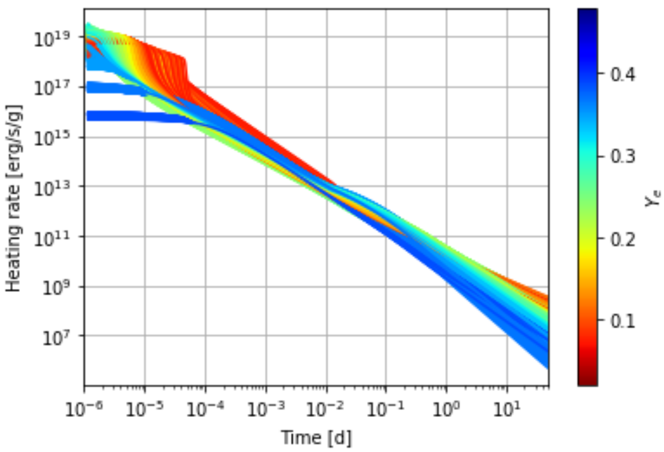

Figure 2. Heating rate fitted trajectories as obtained by performing the fit procedure on a subgrid of thermodynamic variables $0.05 \leq Y_e \leq 0.4$, 3 $\mathrm{k_B}$/baryon $\leq s \leq 50$ $\mathrm{k_B}$/baryon and 1 ms $\leq \tau \leq 30$ ms for visual clarity. Trajectories are color-coded to indicate different initial electron fractions.

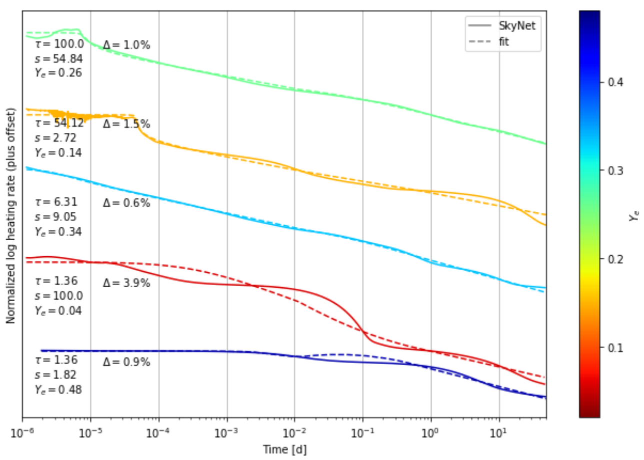

Figure 3. Heating rate SkyNet trajectory along with its fitted version for five different representative sets of thermodynamic variables. Each fit is matched with its relative error defined by equation 4. Trajectories are color-coded to indicate different initial electron fractions.

obtained by using equations 2 and 3, are then joint together with a log-scaled smoothing procedure applied on the time interval 1×10^3 s $\leq t \leq 4 \times 10^4$ s, centered on $t \sim 0.1$ days in log-scale.

Figure 2 shows the fitted version of the heating rate trajectories presented in Figure 1. The quality of a single fit is evaluated using a mean fractional log error, defined as:

$$\Delta(\dot{\epsilon}_{\mathrm{r}}) = \left\langle \frac{|\ln(\dot{\epsilon}_{\mathrm{r}}^{O}(t)) - \ln(\dot{\epsilon}_{\mathrm{r}}(t))|}{\ln(\dot{\epsilon}_{\mathrm{r}}^{O}(t))} \right\rangle, \tag{4}$$

where $\dot{\epsilon}_{\mathrm{r}}^{O}(t)$ is the original SkyNet heating rate trajectory, and the mean is performed over the entire time window 0.1 s $\leq t \leq 50$ days. As visible in Figure 3, our fit procedure returns considerably accurate results: the vast majority of trajectories are reproduced within $\sim 1\%$ relative error, while the worst cases, corresponding to external points in the input grid, carry only a slightly higher error $\lesssim 5\%$.

- Initial and boundary conditions
- Bolometric luminosities and Multicolor luminosities

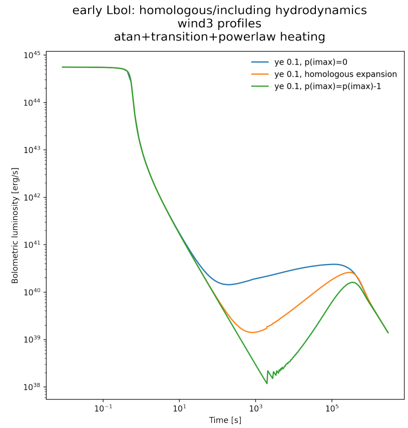

Figure 4. Comparison of homologous expansion and hydrodynamical simulation(ye0.1)

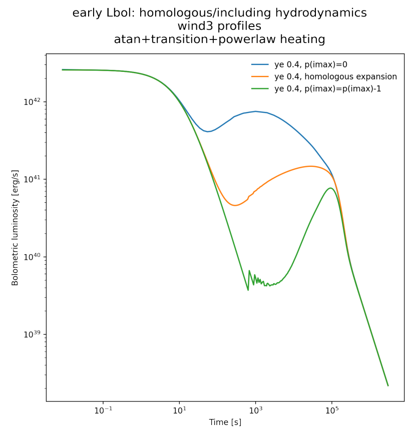

Figure 5. Comparison of homologous expansion and hydrodynamical simulation(ye0.4)

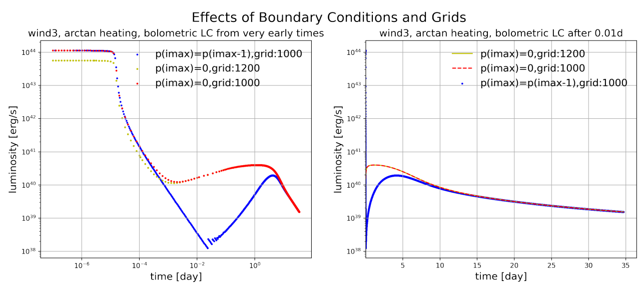

Figure 6. impacts on boundary conditions on bolometric light curves

3 CODE VALIDATION

3.1 Hydrodynamics

Figure 4 5 6 7

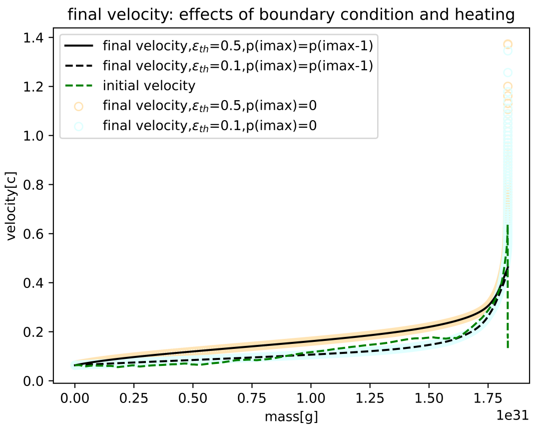

Figure 7. velocity of p(imax)=0 case

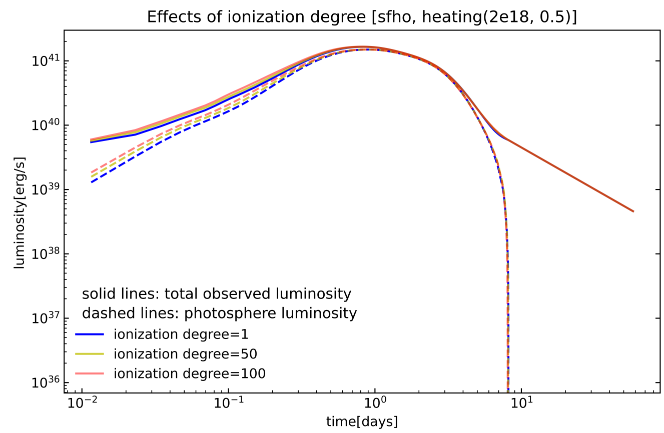

Figure 9. Effects of ionization degree

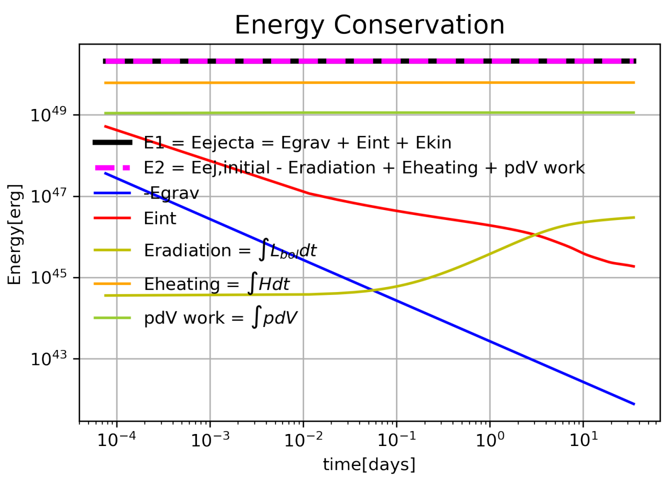

Figure 8. Energy conservation of wind3 ejecta ($0.01M_\odot$, $v_{max} = 0.2c$, $Y_e = 0.05$, $s = 10$ k$_\mathrm{B}$, $\tau = 10$ ms), using $p_{imax} = 0$ boundary condition. E_1 is the total energy of the ejecta, E_2 is the initial ejecta energy + energy from heating - luminosity + pdV work at inner boundary. The maximum difference between E_1 and E_2 is 0.015%.

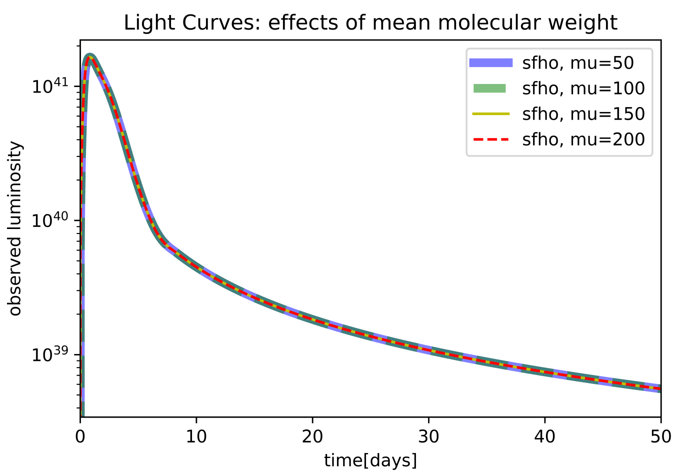

Figure 10. Effects of mean molecular weight

3.2 Energy conservation

In hydrodynamics, energy conservation of a single shell is

$$\frac{D}{Dt}(\rho\epsilon + \frac{1}{2}\rho v^2) = \dot{q} + \boldsymbol{F}\cdot\boldsymbol{v} - \nabla\cdot(p\boldsymbol{v}) \tag{5}$$

where $\frac{D}{Dt} = \frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla$, ϵ is the specific internal energy, $\dot{q}$ is the heat inflow per unit time, $\boldsymbol{F}$ the body force represents gravitational force here. Integrate the whole ejecta, we have

$$\frac{D}{Dt}(E_{int} + E_{kin} + E_{grav}) = \dot{Q} - \int p\boldsymbol{v}\cdot d\boldsymbol{S} \tag{6}$$

$\dot{Q} = H - L_{bol}$, H is the heating from decay of r-process elements and L_{bol} is the bolometric luminosity. For $p_{imax} = 0$ boundary condition, the pdV term $-\int p\boldsymbol{v}\cdot d\boldsymbol{S} = p_1 dV = p_1 v_1 4\pi r_1^2$ Integrate Equation (6) over time, we have cumulative energy conservation shown in Figure 8.

3.3 Comparison with analytic models

4 AB-INITIO SIMULATIONS: FROM MERGERS TO KILONOVAE

4.1 General features

4.2 Impact of EOS

Figure 9 10

4.3 Impact of uncertainties in the heating rates

Figure 11 12 13

5 A FIRST APPLICATION TO AT2017GFO

5.1 Best fitting analytical models

5.2 Comparison between NR informed models and observations

Figure 14 15

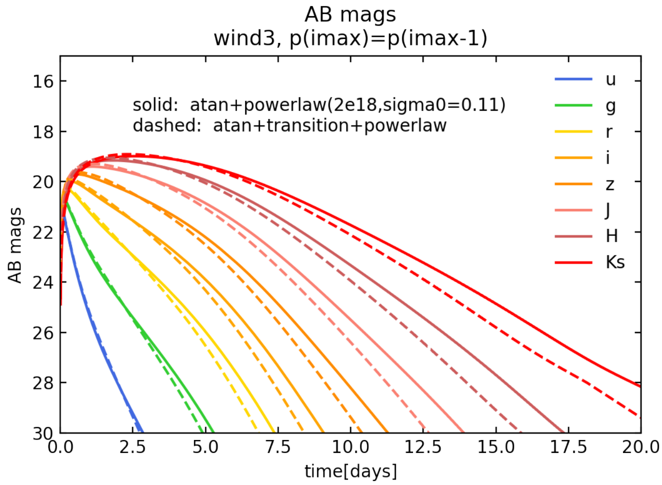

Figure 11. Comparison of multicolor light curves using different heating rates

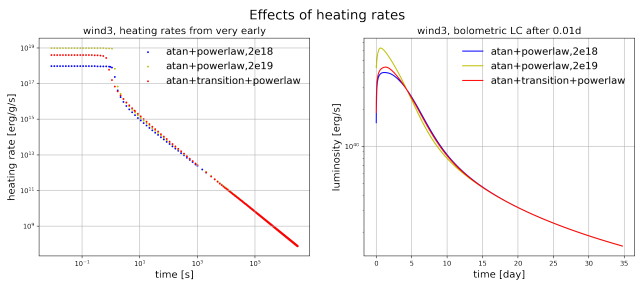

Figure 12. Comparison of bolometric light curves using different heating rates

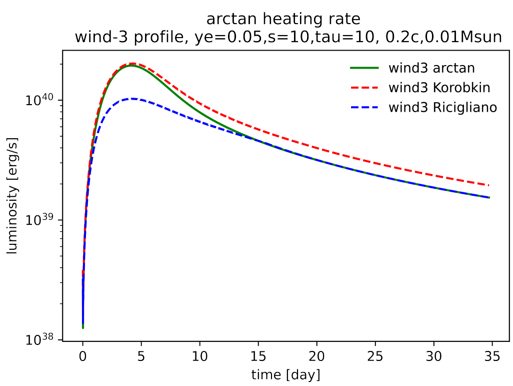

Figure 13. Single powerlaw, atan and Korobkin's

5.3 Impact of shock cooling

6 CONCLUSIONS

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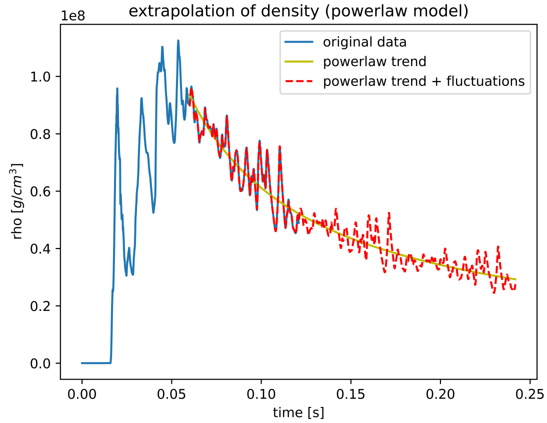

Figure 14. method of extrapolation

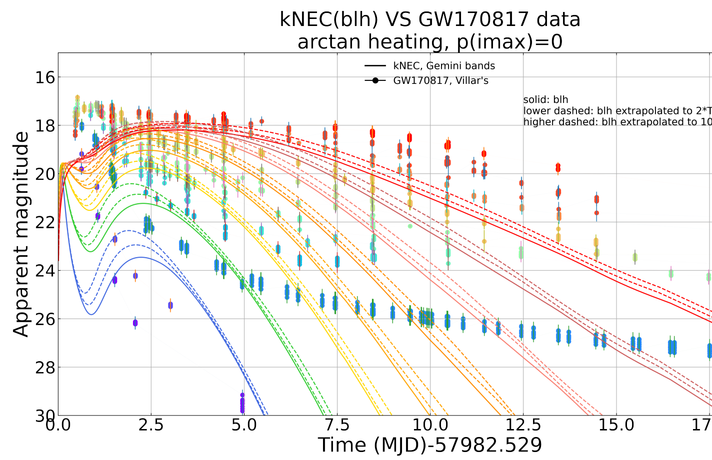

Figure 15. blh extrapolation

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