Contents

1 Introduction

In this letter we examined the energy distribution for model A (run 143), and compared our result with Ohlmann's [2]

2 parameter comparison

In the following table, we listed the initial parameters used by our simulation and Ohlmann's simulation

Quantity	Our Simulation (Run 143, model A)	Ohlmann's Simulation [2]
Mass primary core(M_1)	0.369 $M_\odot$	0.38 $M_\odot$
Mass Envelope gas (M_g)	1.597 $M_\odot$	1.60 $M_\odot$
Mass Red Giant Total (M_{rg})	1.956 $M_\odot$	1.98 $M_\odot$
Mass Secondary core (M_2)	0.978 $M_\odot$	0.99 $M_\odot$
Co-rotation (percentage)	0	95%
Radius of envelope (RG) (R_g)	$48.1R_\odot$	Unspecified ($\approx 49\ R_\odot$[1])
Initial separation between cores (a_0)	49 $R_\odot$	49 $R_\odot$
Box side length (R)	1150 $R_\odot$	$3.3 * 10^{14}$ cm ($\approx 4744.78\ R_\odot$)
Softening radius (r_s)	2.4 $R_\odot \rightarrow$ 1.2 $R_\odot$	$7.3 * 10^{10}$ cm ($\approx 1.0\ R_\odot$)
Ambient density (ρ_a)	$6.67 * 10^{-9}$ g cm^{-3}	10^{-16} g cm^{-3}
Ambient pressure (P_a)	$1.01 * 10^5$ dyn cm^{-2}	Unspecified

As can be seen from the table, the initial values of our simulation is pretty close to those used by Ohlmann.

3 Theory

In this section we present the theory of different kinds of energies. For this project, we consider the system as a classical system.

3.1 Kinetic energy

The kinetic energy of two particles with mass m_1, m_2 in a two-body problem is given by

$$T_p = \frac{1}{2} m_1 \overrightarrow{v_1}^2 + \frac{1}{2} m_2 \overrightarrow{v_2}^2 = \frac{1}{2} \mu \overrightarrow{v}^2 \tag{1}$$

where

$$\mu = \frac{m_1 m_2}{m_1 + m_2} \quad \text{and} \quad \overrightarrow{v} = \overrightarrow{v_1} - \overrightarrow{v_2} \tag{2}$$

The Kinetic energy of gas is dependent on the location of the gas. Therefore we need to find the kinetic energy of gas at each location and integrate over its volume. Therefore

$$T_g = \frac{1}{2} \int_V \rho(\overrightarrow{r}) v(\overrightarrow{r})^2 dV \tag{3}$$

3.2 Internal energy

The thermal energy of a fluid is

$$E_{\text{int}} = \frac{1}{\gamma - 1} \int_V P(\overrightarrow{r}) dV \tag{4}$$

where γ is the adiabatic index

3.3 potential energy

The potential energy between two particles in Newtonian mechanics is

$$U_p = -G\frac{m_1 m_2}{|\overrightarrow{x_1} - \overrightarrow{x_2}|} = -G\frac{m_1 m_2}{|\overrightarrow{r_{12}}|} \tag{5}$$

To find the potential energy of the gas itself, We can find the potential due to gas as a function of location $\Phi(\overrightarrow{r})$ and multiply that by the density of the gas at that location. The potential energy is given by

$$U_g = \frac{1}{2}\int_V \Phi(\overrightarrow{r})\rho(\overrightarrow{r})dV \tag{6}$$

The potential energy between gas and particle can be obtained by taking the gravatational potential due to the particle $\Phi_p(r_g)$, mutiply by gas density and sum over all space

$$U_{p,g} = \int_V \Phi_p(\overrightarrow{r_g})\rho(\overrightarrow{r_g})dV \tag{7}$$

where r_1 is the location of m_1

4 Method

Energy of a system can be divided into three categories: kinetic energy, potential Energy and internal energy. We will present them one-by-one

4.1 Kinetic energy

The kinetic energy is composed of by the kinetic energy of the cores and the kinetic energy of the gas. In our simulation, the gas was treated as a fluid, so we will use equation for fluid dynamics to calculate the energy of the system.
The kinetic energy of the cores is given by the Newtonian kinetic energy

$$T_c = \frac{1}{2}m_c v_c^2 \tag{8}$$

And the gas kinetic energy density is given by

$$\mathscr{E}_{g-kin} = \frac{1}{2}\rho_g v_g^2 \tag{9}$$

And we sum it over the box to get the total kinetic energy f the gas.
Total kinetic energy is given by

$$T_{tot} = T_{c(1)} + T_{c(2)} + \int \mathscr{E}_g dV \tag{10}$$

4.2 Internal energy

Due to the lack of a sub-grid model, the internal energies of the cores are both zeros. Therefore the only component of internal energy is the internal energy of the gas (envelope)
By setup, the simulation output the sum of kinetic energy and internal energy. Therefore a quick way to calculate the internal energy is to use the output energy E_{output} subtract the kinetic energy

$$I_{tot} = I_{gas} = E_{output} - T_{gas} \tag{11}$$

4.3 Potential energy

The potential energy is the most tricky one. The potential energy is divided into three sub-catagories: core-core potential energy, gas-self potential energy and core-gas potential energy. Softening radius also effect the way we calculate the potential energy, which we will be discuss in more detail later
Because the cores never enter the softening radius of each other, the potential energy between the cores is given by the Newtonian potential energy

$$U_c = -G\frac{M_1 M_2}{r_{12}} \tag{12}$$

To compute the gas-self potential energy, we can use directly the output of the simulation. In the output, we have the potential due to gas as a function of a radius $\Phi_g(r)$. To obtain the potential energy, we only need to find the potential energy density and integrate over the entire box. The energy density is given by

$$\mathscr{E}_{g-pot}dV = \frac{1}{2}\rho\Phi_g(r)dV \tag{13}$$

In the figure right now, this term is not considered. Another term that we need to consider when analyzing the simulation is the self-gravity of gas within each cell. Because $\mathscr{E}_{g-pot}$ takes each cell as a point particle, an additional term is needed to calculate the potential within each cell [6]. Given all cells are cubes, the equation for self-gravity in each cell is

$$\mathscr{E}_{g-pot-cell} \approx 0.941 G\rho^2 L^5 \tag{14}$$

where ρ is the density of each box and L is the side length
Therefore, the total self-grvity is

$$U_g = \int \mathscr{E}_{g-pot-cell}dV + \sum \mathscr{E}_{g-pot} \tag{15}$$

The final term to consider for potential energy is the gas-partial potential energy. Because of the existance of softening radius, the potential energy doesn't go as $-G\frac{Mm}{r^2}$ inside the softening radius. Therefore we need to divide into two regions: outside the softening radius and inside the softening radius.
Outside the softening radius, the gravitational potential due to the cores is given by

$$\Phi_{c,out}(r) = -G\frac{M}{r} \tag{16}$$

Inside the softening radius, we have two regions of refinement: region 1: between $0.5r_{\text{soft}}$ and r_{soft}; region 2: inside $0.5r_{\text{soft}}$ [7]
Now define a normalization factor for the distance from the core $\vec{\mathbf{r}}$

$$u = \frac{|\vec{\mathbf{r}}|}{|\vec{\mathbf{r}_{\mathbf{soft}}}|} \tag{17}$$

In region 1, define spline 1, the modify term for gravitational potential in region 1 as

$$S_1 = -\frac{16}{3}u^3 + \frac{48}{5}u^5 - \frac{32}{5}u^6 + \frac{14}{5}u \tag{18}$$

In region, define spline 2, the modify term for gravitational potential in region 2 as

$$S_2 = -\frac{1}{15} - \frac{32}{3}u^3 + 16u^4 - \frac{48}{5}u^5 + \frac{32}{15}u^6 + \frac{48}{15}u \tag{19}$$

And by region, we define our gravitational potential by the cores as

$$\Phi_c = \begin{cases} \Phi_{c,out} & r_{\text{soft}} \le r \\ \Phi_{c,out} \times S_1 & 0.5\ r_{\text{soft}} \le r < r_{\text{soft}} \\ \Phi_{c,out} \times S_2 & r \le 0.5\text{r}_{\text{soft}} \end{cases} \tag{20}$$

Using same logic as previous calculation, the potential energy between the gas and cores is given by

$$U_{gc} = \int \rho_g \Phi_c dV \tag{21}$$

And total potential energy is the sum of all three terms

$$U_{tot} = U_c + U_g + U_{gc} \tag{22}$$

4.4 Total energy

With kinetic energy, internal energy and potential energy being calculated, we can now determine the total energy of the system

$$E_{tot} = T_{tot} + U_{tot} + I_{tot} \tag{23}$$

Note that when E_{tot} is greater than zero, the *system* will become unbound. Because the cores clearly bounds to each other, unless the energy of the gas overwhelms the energy of the core, we expect that the total energy to be negative.

5 Reduced Resolution data

5.1 Time dependence of energy

We present here result from our simulation and result provided by Ohlmann's paper

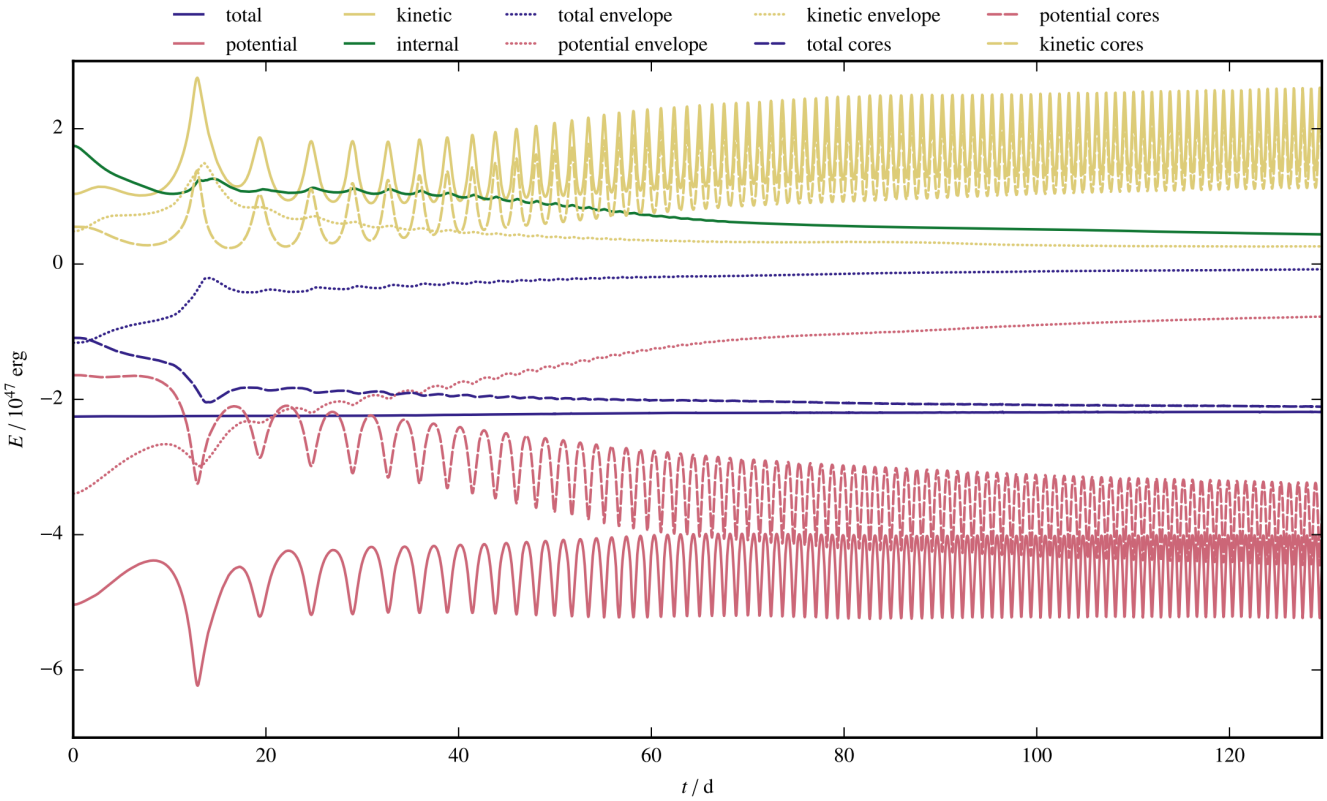


Figure 1: Energy diagram provided by Ohlmann's paper, note that in his simulation the simulation time goes to 120 days, whereas in the next figure, our simulation only goes to 40 days.[2]

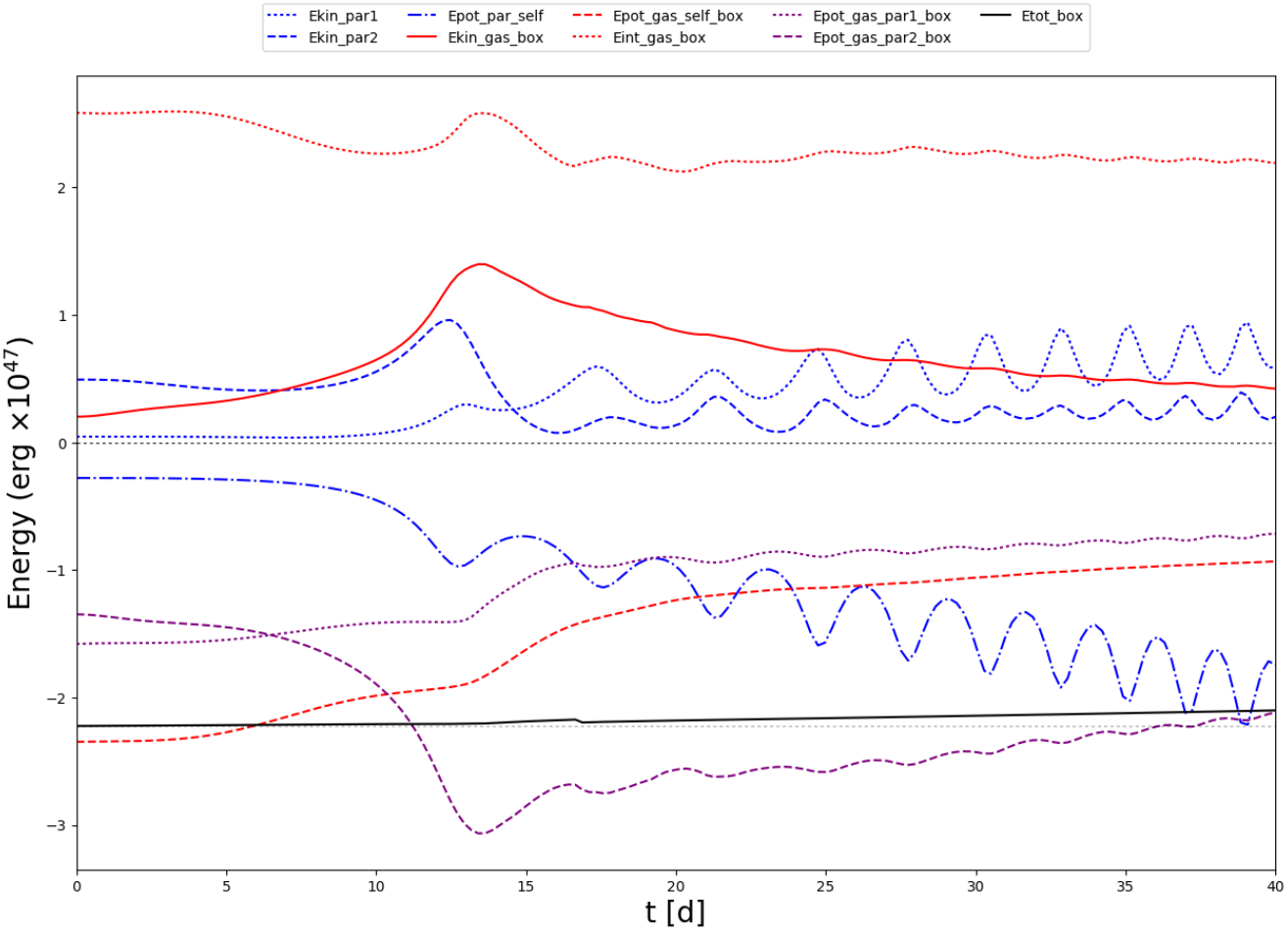


Figure 2: Energy diagram from our simulation. The figures are energy plots from our simulation, this is the original data, Equations to calculate some terms are shown in appendix A updated 07/28/2018

It's been noted that the ambient medium has an non-negligible mass and pressure. The total mass of the ambient medium is $M_{amb} = 6.67 * 10^{-9} * (8 * 10^{13})^3 = 3.41 * 10^{33}\text{g} = 1.717 M_\odot$, more then half of the mass of the RG and secondary combined!
The total energy changes by $1.252 * 10^{46}$erg (5%). If we take into account the fact that the solfening radius is reduced by a half during the simulation, the total energy change will be $1.481 * 10^{46}$erg. (5.92%)
To estimate the effect of ambient medium on the evolution, one of the method is to estimate the initial total energy of the ambient and subtract that from the energy of the gas. Because in the first frame, the ambient medium is not moving ($v = 0$ and $T_{amb} = 0$), we only need to consider potential energy and internal energy. In the first frame, the density and pressure of the ambient material are both constants through out, therefore the internal energy of the material is given by

$$E_{\text{int, amb}} = \frac{3}{2} PV = \frac{3}{2} * 10^5 * (8 * 10^{13})^3 = 7.68 * 10^{46}\text{erg} \tag{24}$$

The potential energy of the self-gravity of the material is

$$U_{amb} = \int_L^H \int_L^H \int_L^H \int_L^H \int_L^H \int_L^H -G \frac{\rho^2}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}} dx dy dz dx_0 dy_0 dz_0 \tag{25}$$

where $L = -4 * 10^{13}$ and $H = 4 * 10^{13}$, the boundaries of the box.
This equation is too computational intensive to solve, therefore I believe we can consider the following.

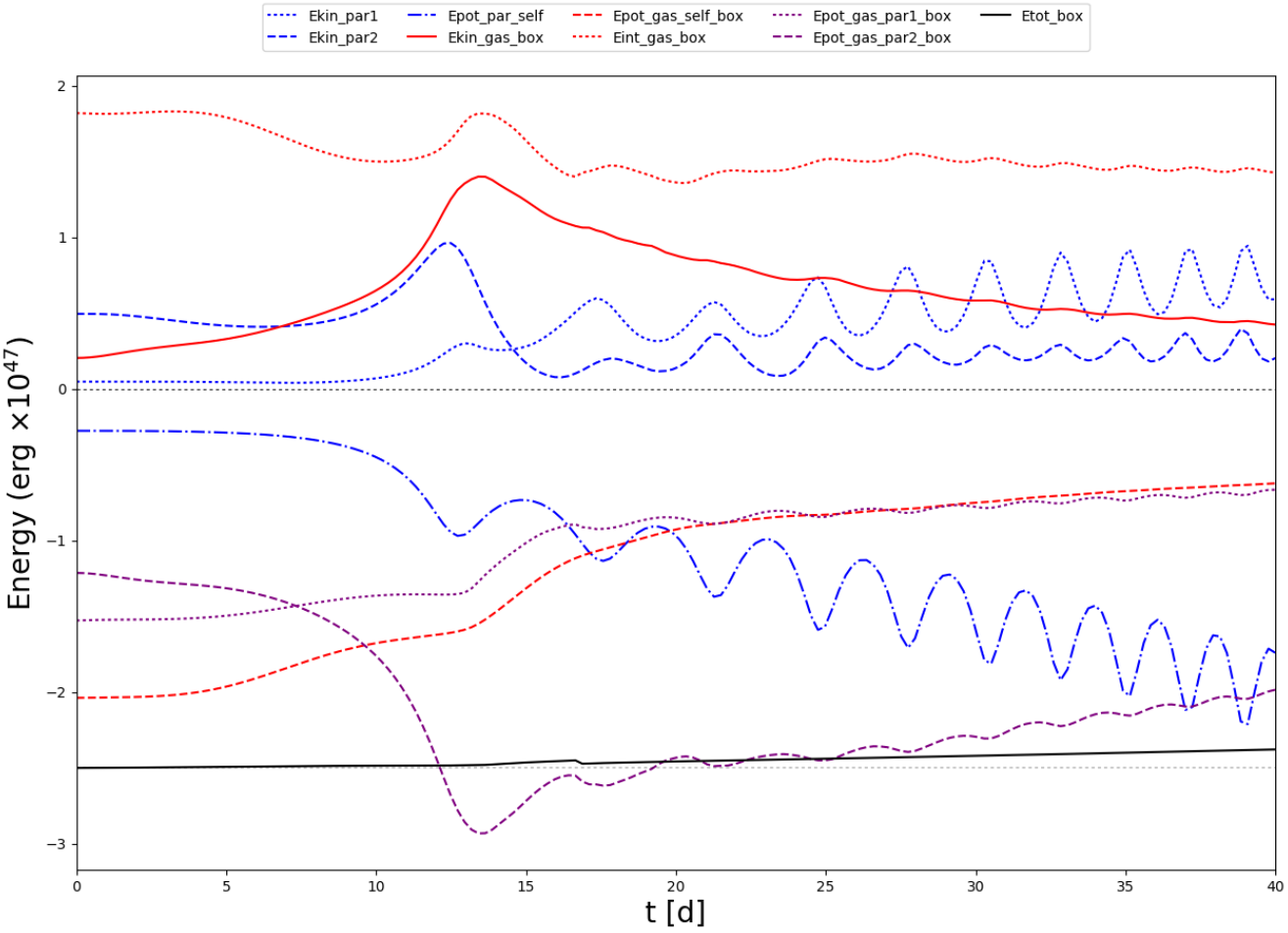


Figure 3: Energy diagram from our simulation. The figures are energy plots from our simulation with ambient removed, this is the original data, Equations to calculate some terms are shown in appendix A

The self-gravity potential will be less than a sphere that exactly fit in the box, and will be greater than a sphere that can exactly contain the box. Then, the limits are simply

$$U_{lim} = -\frac{3}{5}\frac{GM^2}{R} \quad \longrightarrow \quad U_{\text{upper}} = -1.17 * 10^{46}\text{erg} \qquad \text{and} \qquad U_{\text{lower}} = -6.74 * 10^{45}\text{erg} \tag{26}$$

This value appears to be less significant than the internal energy.
And the potential energy between the ambient material and the cores are

$$U_{\text{amb, core}} = \int_L^H \int_L^H \int_L^H -G\frac{\rho m_c}{\sqrt{(x-x_c)^2+(y-y_c)^2+(z-z_c)^2}} dxdydz \tag{27}$$

And the values are ##### $U_{amb,core2}$ is crashing when I try to calculate it... So I calculate the value if the second core is at the center#####

$$U_{\text{amb, core1}} = -4.97375 * 10^{45}\text{erg} \quad \text{and} \quad U_{\text{amb, core2}} = -1.31825 * 10^{46}\text{erg} \tag{28}$$

Another term that we need to consider is the gravitational interaction between the ambient material and the actual gas in the box. To calculate this potential, we need to integrate over our actual gas (which is no longer a perfect

sphere after the first frame) and integrate over the whole box. This calculation is again too computational intensive, but because the gas is concentrated in the center of the box, we can approximate it to a point particle at the location of its center of mass. With this approximation, the gravitational potential that we found is

$$U_{amb,gas} \approx \int_L^H \int_L^H \int_L^H -G\frac{\rho m_{gas}}{\sqrt{(x-x_g)^2+(y-y_g)^2+(z-z_g)^2}}dxdydz = -2.1526*10^{46}\text{erg} \tag{29}$$

Note that this approximation breaks down after the first few frames, but we use this value to generate the plot.
To estimate the effect of ambient material to the envelope evolution, we have to take into account that the gas "wasted" some energy to push the ambient outward. There are two terms to consider: work acting against ambient pressure and work acting against ambient gravity.
First consider work acting against pressure. Approximate the initial position of the gas are all around the center region, assuming that the pressure doesn't change during the simulation (As we checked, the pressure changes by less than $2\times$) and assuming that the ambient medium has been pushed to a sphere with radius half the box width (This is an overestimate of the distance), we have energy used equal to

$$E_{\text{push-bound}} = P_0 * \int_0^{4*10^{13}} 4\pi r^2 dr = 1.34*10^{46}\text{erg} \tag{30}$$

In the simulation, the gas tends to be pushed to a sphere radius $3*10^{13}$ cm from the center. In this case, the energy dissipated is

$$E_{\text{push-3e13}} = P_0 * \int_0^{3*10^{13}} 4\pi r^2 dr = 0.565*10^{46}\text{erg} \tag{31}$$

Now consider work against gravity. Assuming that the rest of the mass (the stars) are located at the center with a constant mass, the gravitational potential to move a layer thick dr of ambient at the radius r is given by

$$\mathscr{E}_{\text{push-grav}}dr = G\frac{\rho 4\pi r^2 dr}{r} - G\frac{\rho 4\pi r^2 dr}{r_{\text{final}}} = 4\pi G\rho\Big(r - \frac{r^2}{r_{\text{final}}}\Big)dr \tag{32}$$

Then, to move everything inside radius $3*10^{13}$ cm to that radius, we need energy equal to

$$E_{\text{push-grav}} = 8.38596*10^{11}\text{erg} \tag{33}$$

This is an estimate of the energy used. In practice the ambient is accelerated to a non-zero velocity, meaning the gas has some kinetic energy. But unless the velocity is large (which is not likely), the energy will keep on this order of magnitude and be negligible comparing to those in orders of magnitude 10^{46}.
From the calculation, we can estimate that the total potential energy by the ambient gas is around $-0.4*10^{47}$ erg, and that the total energy of the ambient is dominated by the internal energy. The range of total energy of ambient gas is between $2.4*10^{46}$erg and $3.2*10^{46}$erg.
The final envelope total energy (excluding self-gravity) is $-8*10^{46}$ erg. If we add the work "wasted" by the gas, the final envelope total energy will become $-6.66*10^{46}$ erg.

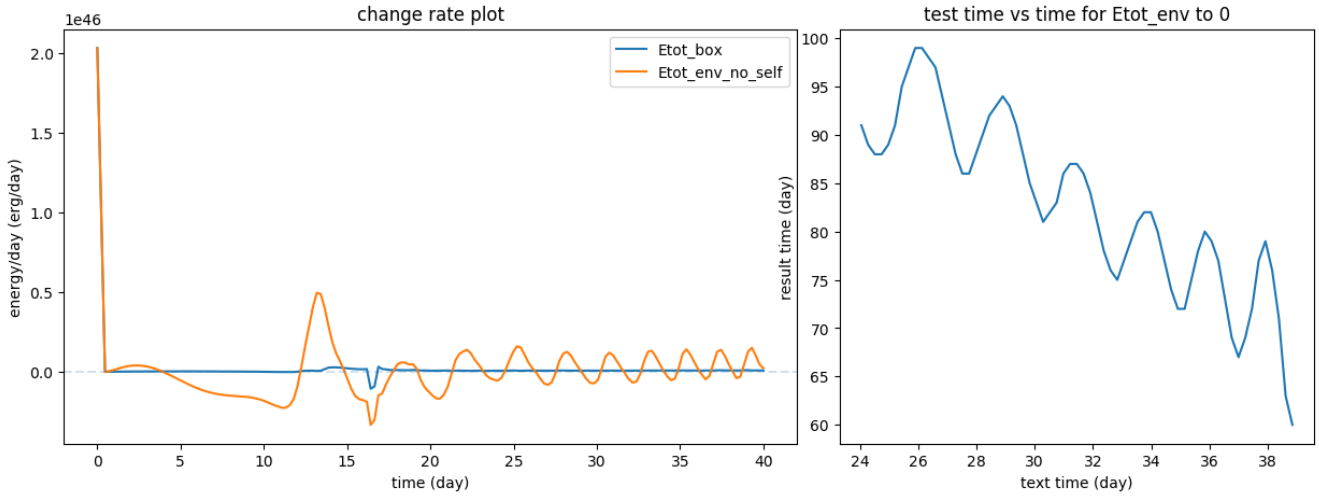


Figure 4: Left is the gradient of total energy and Etot_env_no_self. Right is the estimated time for Etot_env_no_self to go to zero vs the number of test data points that we take from the end of Etot$_e nv_n o_s elf$

It appears, from the preceding figures, that the acceleration is majorly above zero, meaning energy is mainly increasing. The figure to the right appears that the shorter we take, the faster it will be for the value to go to zero.

The change in total kinetic energy from frame 0 to 1 is equal to $2.037 * 10^{46}$erg. It is likely that this change is due to absence of velocity term of gas in first frame. If we include the fact that the velocity of gas is $-3.563 * 10^6$ cm/s and anything within radius $3.35 * 10^{12}$ cm from the center moves at this speed, using Bluehive, we get the following kinetic energy:$2.027 * 10^{46}$erg. The difference between this value and the energy in the first frame is 0.4%. If we replot figure 2, then the problem in the first frame is fixed. The effect of some values in previous 2 pages are marked in red. The Python file for the followig plot names Get0thFrameGasKineticEnergy.py

5.2 Theory and simulation value comparison

5.2.1 Values comparison

Description	Semi-analytic	Simulation	diff	agree?	note
Energy involving particle only					
Initial particle 1 kinetic energy	0.05	0.046	0.004	✓	
Initial particle 2 kinetic energy	0.49	0.494	-0.004	✓	
Initial particle kinetic energy	0.54	0.540	0.0	✓	
Initial inter-particle potential energy	-0.28	-0.278	-0.002	✓	
Final inter-particle potential energy	-1.95	-1.743	-0.2069	✓	(II)
Gas energy budget					
Initial envelope bulk kinetic energy	0.20	0.203	-0.003	✓	
Initial envelope internal energy	1.81	1.817	-0.0069	✓	(I)
Initial envelope particle 1 potential energy	-1.56	-1.529	-0.031	○	(I)
		-1.529	*-0.031*		*(VI)*(VIII)
		-1.547	-0.013		(VII)(VIII)
Initial envelope particle 2 potential energy	-1.21	-1.216	0.006	✓	(I)
		-1.216	*-0.006*		*(VI)*
		-1.216	-0.006		(VII)
Env-par2 pot energy if par 2 at RG center	-4.14				
Initial envelope potential energy, self gravity	-2.13	-2.039	-0.0909	○	(I)
Initial ambient medium internal energy	0.77 (0.768)	0.768	0.002	✓	(V)
Initial ambient medium-particle 1 pot energy	-0.05 (-0.0497)	-0.025	-0.0243	×✓	(III)
Initial ambient medium-particle 2 pot energy	-0.13 (-0.138*)	-0.066	-0.072	×✓	(III)
Initial ambient medium envelope potential energy	-0.22 (-0.215)	???			
Initial ambient medium pot energy, self-grav	-0.09 (-0.0922)	-2.34			
Initial gas-particle 1 potential energy					
Initial gas-particle 2 potential energy					
Initial gas pot energy due to self-grav					
Initial envelope binding energy (< 0 = bound)					
RG core-env PE only	-1.56	-1.529	-0.0310	○	(I)
		-1.529	*-0.031*		*(VI)*
		-1.547	-0.013		(VII)
RG core-env PE + intern	0.25	0.289	-0.0389	✓	(I)
RG core-env PE + Env-env PE + intern	-1.87	-1.750	-0.120	○	
RG core-env PE + intern + env bulk KE	0.46	0.492	-0.0319	○	
RG core-env PE + Env-env PE + intern + env bulk KE	-1.67	-1.548	-0.1219	○	(I)
RG core-env PE + Sec-env PE	-2.77	-2.744	-0.0259	✓	(I)
RG core-env PE + Sec-env PE + Env-env PE	-4.90	-4.784	-0.116	✓	(I)
RG core-env PE + Sec-env PE + intern	-0.96	-0.926	-0.0339	✓	(I)
RG core-env PE + Sec-env PE + intern + env bulk KE	-0.76	-0.724	-0.036	✓	(I)
RG core-env PE + sec-env PE + Env-env PE + intern	-3.09	-2.966	-0.1239	○	
ANS + env bulk KE	-2.89	-2.763	-0.1270	○	
As above but with secondary at center of RG	-5.82	N/A			
Liberated from change in orbital energy					
Ivanova et al. (2013) eq (3) RHS					
Initial orbital energy	-0.75	-1.494	0.744	×✓	(IV)
Final orbital energy	-0.97	-1.743	0.773	×✓	(IV)
Initial orbital energy of particle only	-0.14	-0.278	0.138	×✓	(IV)
By particles only	0.83	1.465	-0.6350	×✓	(IV)

5.2.2 Explanations for disagreements

I) The simulation values are calculated using the data from simulation and subtract the value in parenthesis in Semi-analytic column. The calculation of these values are in Energy note.

II) The difference in r_{final} caused the problem. The particles are in elliptical orbits, and it's hard to define a r_{final} for elliptical orbit

III) The simulation calue reported cut areas within radius $3.35 * 10^{12}$, whereas in calculation all areas are included. This is a calculation independent of other calculations.

IV) They are differ by about a factor of two because the simulation value didn't account for kinetic energy. However, for final orbital energy, the particle is in elliptical orbit, so Virial Theorem doesn't work in this case (not a factor of 2)

V) This value is actually term E in chombo file. Because we know E_kin in the first frame is 0 in the file (disregard our correction), $E = E_{int}$

VI) This value is computed directly using VisIT. A function called is 'clip'. I cut out all regions beyond $3.35 * 10^{12}$cm, and calculated the potential energy due to the gas left. This value considers the spline potential. (Calculated using de-resolved data)

VII) This value use the same method as previous one. This value did NOT consider the spline potential (Calculated using de-resolved data).

VIII) It turned out that the mass inside the sphere is smaller than we expected (By VisIT, the mass inside sphere $r = 3.35 * 10^{12}$ is $1.606 M_{\odot}$. The theoretical value is $1.597 M_{\odot}$. Since in Theory, a larger mass would result in a potential tnat is more negative, the distribution of mass may not be the same as we believed. A task maybe possible would be calculating the mass distribution and comparing with our template.

5.3 Spacial dependence of energy

5.3.1 Normalized energy figures

The following figures shows the normalized energy function. The function used to normalize the function is

$$N_{\mathbf{r}} = \frac{E_{\mathbf{r}}}{\max(|KE + E_{\text{int}}|, |PE_{\text{gas\_par}} + PE_{\text{gas\_gas}}|)} \tag{34}$$

where E_r is the total energy as a function of radius including gas self-potential energy

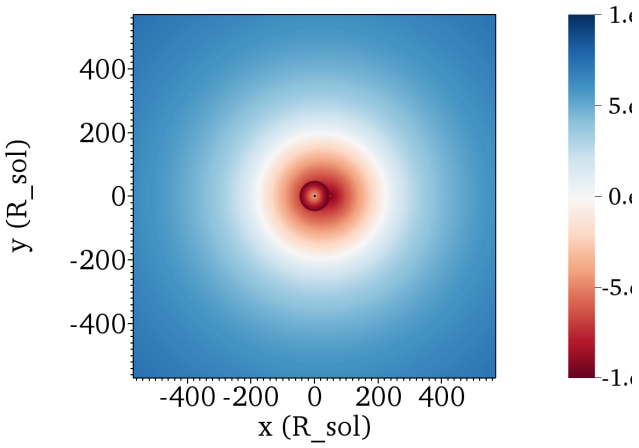
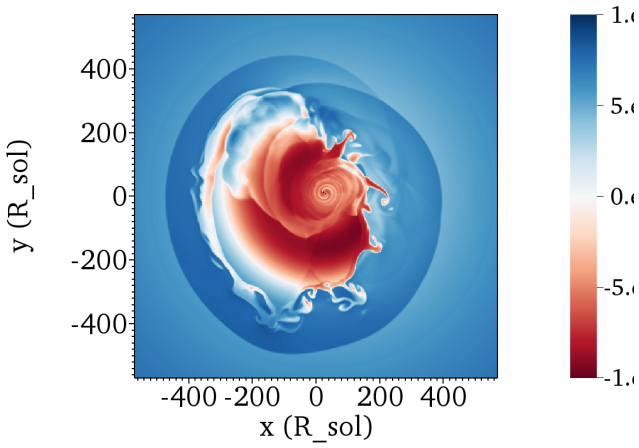


Figure 5: Initial energy distribution in x-y plane



0.5

Figure 6: Final energy distribution in x-y plane

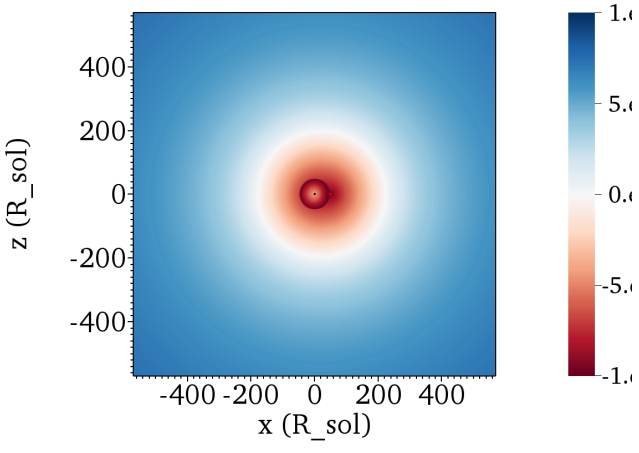


Figure 7: Initial energy distribution in x-z plane

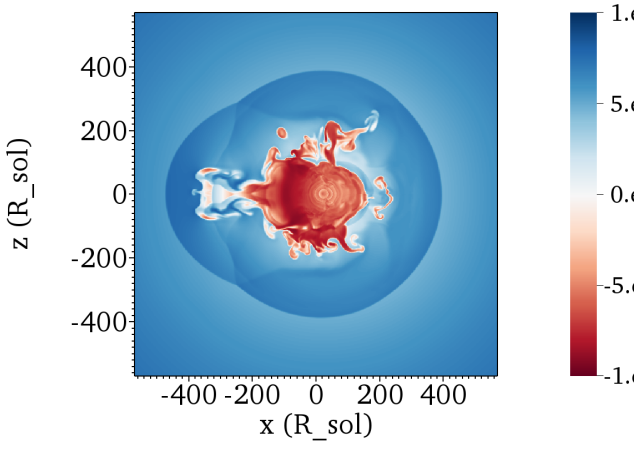


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Figure 8: Final energy distribution in x-z plane

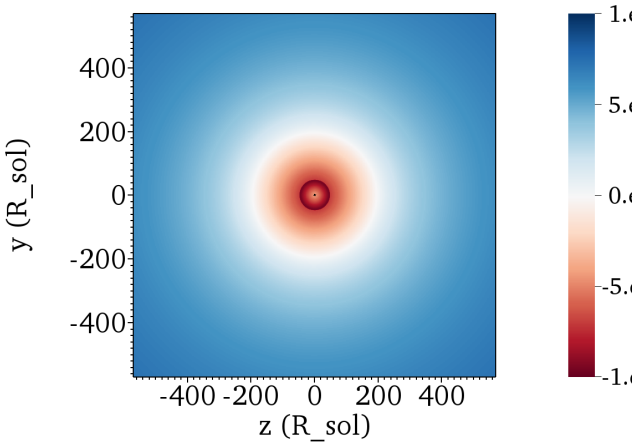
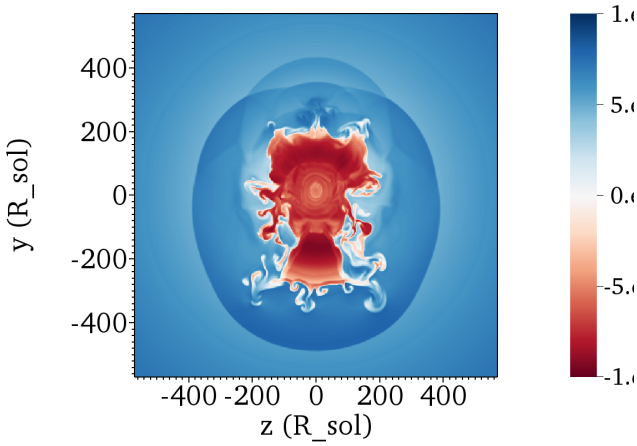


Figure 9: Initial energy distribution in y-z plane



0.5

Figure 10: Initial energy distribution in x-y plane

The result gives us the sign of the gas and the difference between the positive energies and negative energies. The actual values of energy is distributed widely, so this is the way for us to understand the spacial distribution. In figure 6, we see that the clear spiral structure. There are actually material with escape velocity keep ejected from the neighborhood of the cores, and they interact with the surrounding material losing some energy. Some earlier figures show that there can be an "onion" ring structure suggesting that unbound and bound gas form layer structure.

It is also worth noticing the initial ambient material is unbound.

I have plots for all frames in all three direction for normalized and original data. It would be informative to see some of the evolution. Though putting 174 frames in this Latex file is impossible..

5.3.2 Radial Energy distribution

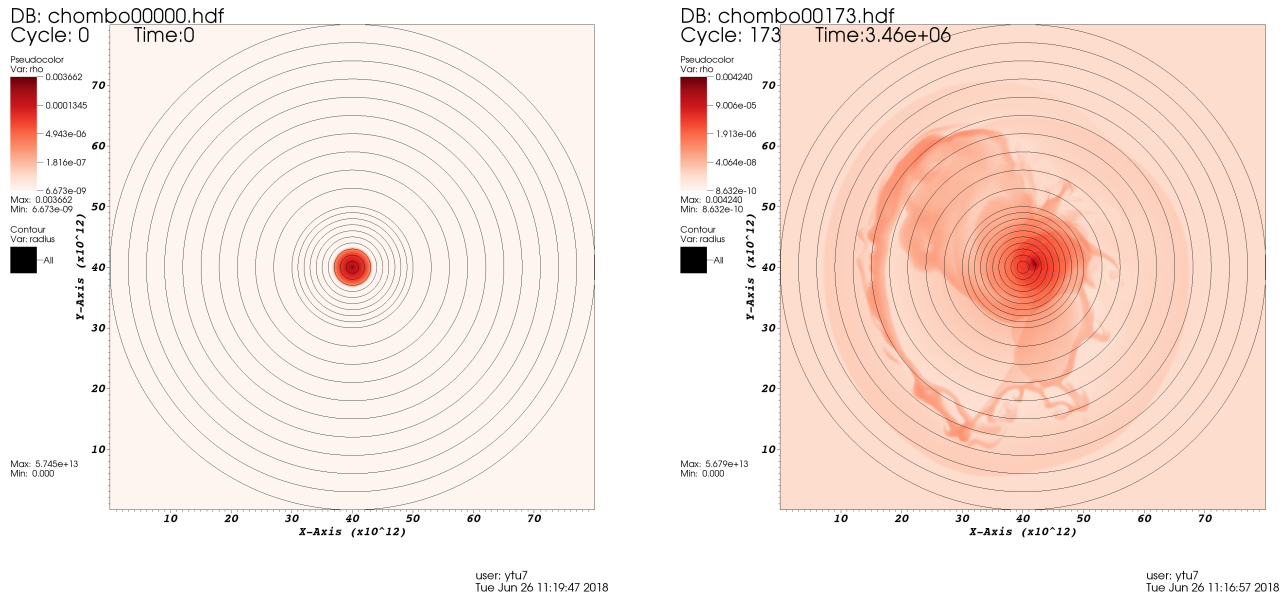


Figure 11: contours showing the radial shells that are presented next

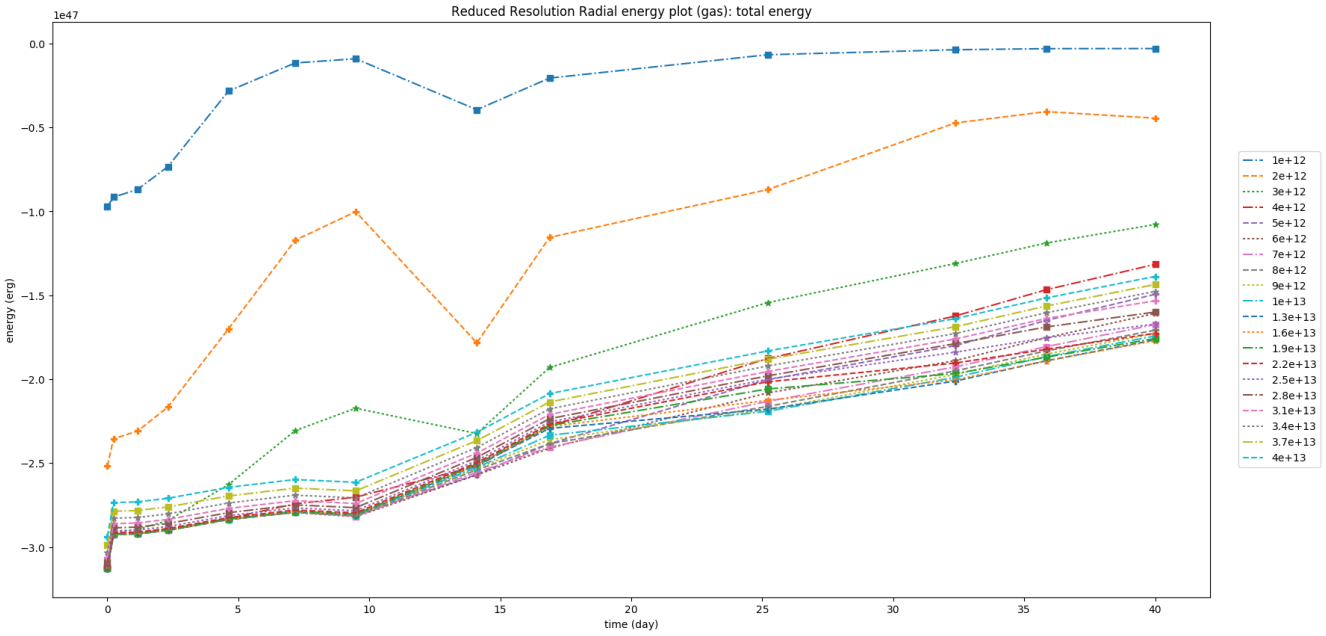


Figure 12: total energy distribution as a function of radius and time. The curves are cumulative: The outer radius includes all in the smaller radius.

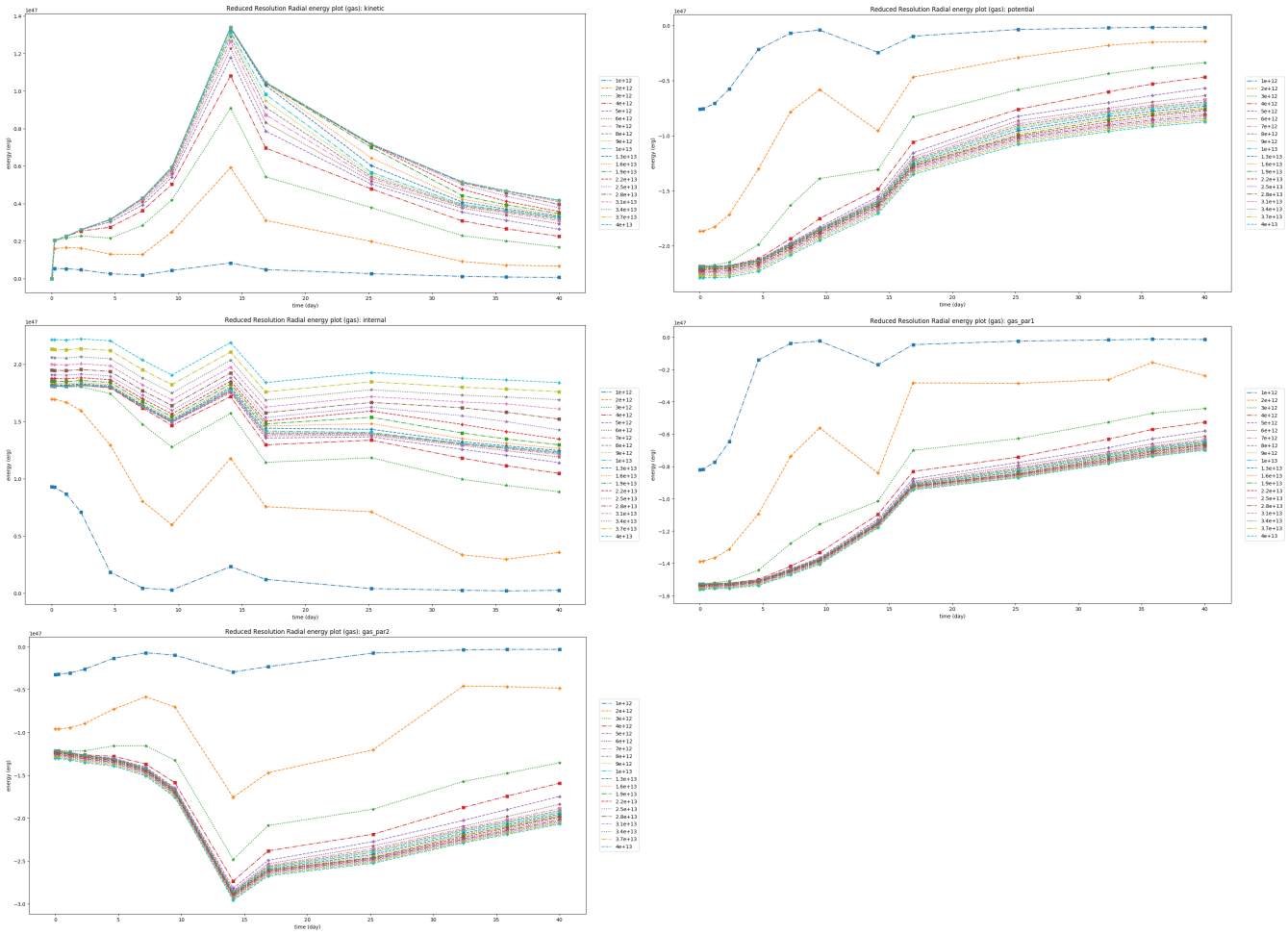


Figure 13: components for total energy as a function of radius and time. upper left: kinetic, upper right: potential; middle left: internal; middle right: gas and particle 1 potential; bottom left: gas and particle 2 potential.

These figures are radial distribution of energy for reduced resolution data set. Because the program is too computationally intensive, I only collected data from several frames where something interesting seems to be happening according to mass radial distribution plot (see later). The data points are marked on the figure. The blue line is the inner-most, and other lines move out respectively.

It appears that the energy is somewhat concentrated in the most central region. The potential energy and kinetic energy doesn't increase too much by moving outward a lot (10 lines). The ambient medium doesn't seem to have a lot of energy as the center do.
The most central region doesn't seems to have too much energy, however, the regions near the center $2e13$ to $3e13$ seems to be where energy concentrates. This also agrees with radial pseudocolor plot presented earlier.

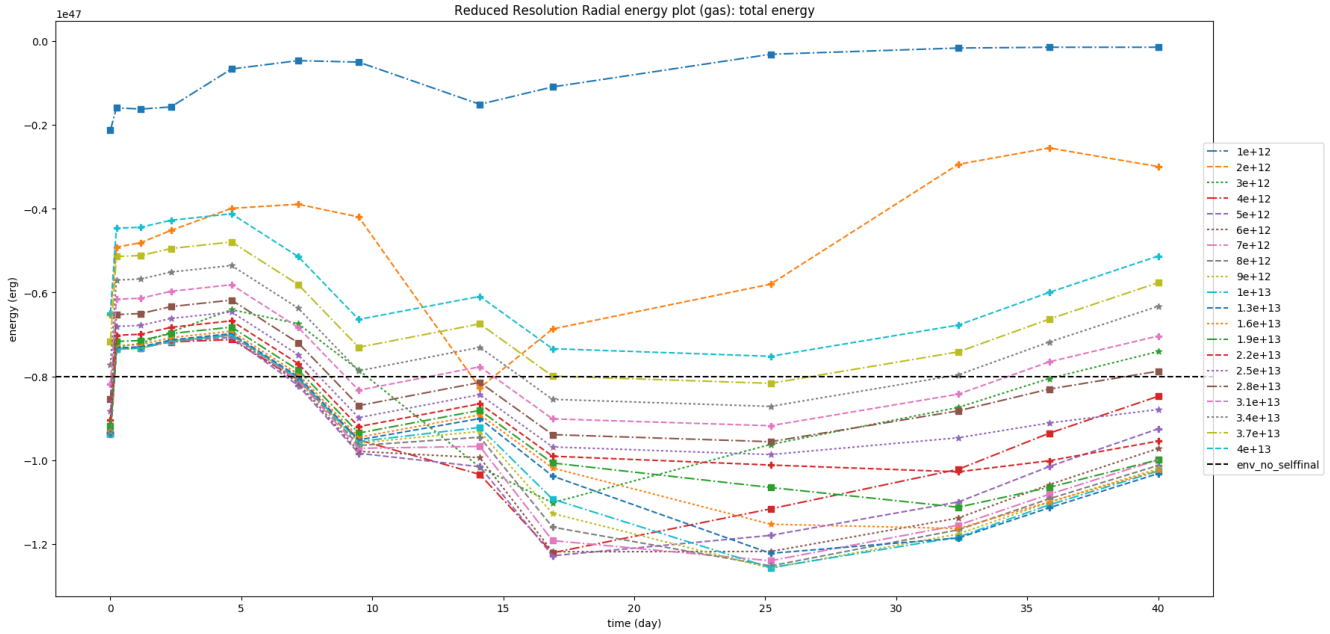


Figure 14: Same figure as previous one but with self-gravity removed. The horizontal black dahsed line is the final value of Etot_env_corrected_no_self in Ohlmann comparison figure. 2

An interesting phenomenon in this figure is that the bottom line is actually not the outer-most line, which means that in some region in the middle, the gas actually has positive energy. The most bottom lines are $1 * 10^{13}$cm, $4 * 10^{12}$cm and $5 * 10^{12}$cm. So some rings above $1 * 10^{13}$ must have positive energy.

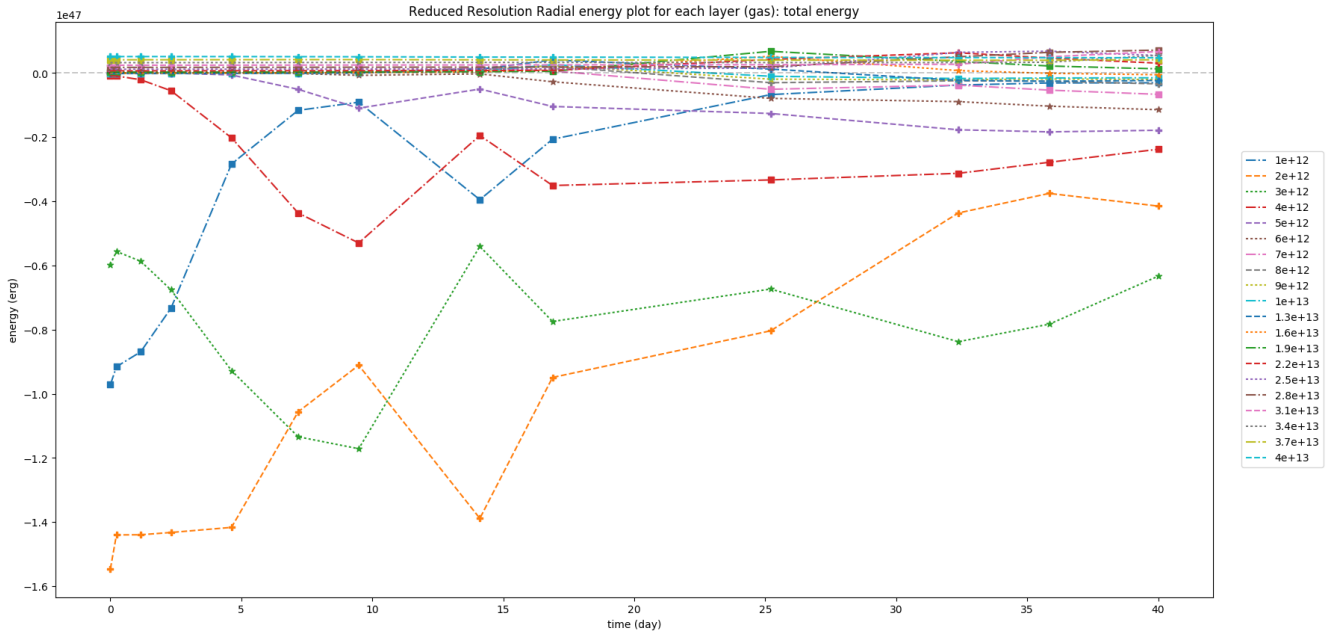


Figure 15: The energy between each adjacent layers. The values shown here are values between the one shown and the one layer just below it.

5.4 Energy and orbital radius

5.4.1 Energy in orbital radius

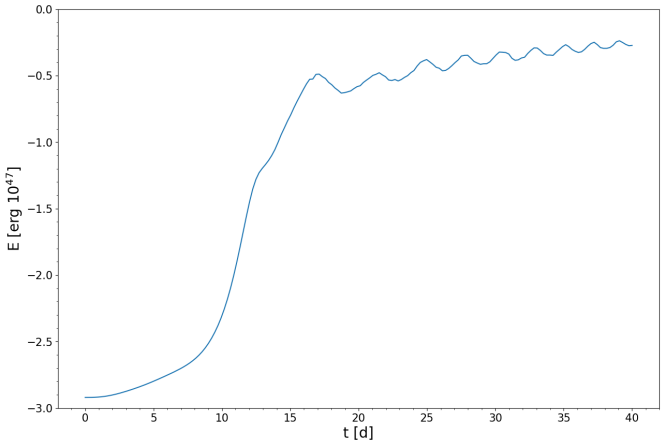


Figure 16: The energy with in orbit around particle 1. "inside" is defined as a sphere centered at particle 1 and radius as the separation between particle 1 and 2.

From this plot, it appears that the amount of energy within the orbit is not significant compared to the total energy. The initial energy satisfying this criteria is $-2.92*10^{47}$erg; The final energy satisfying this criteria is $-0.273*10^{47}$erg The first frame had some problem yielding the data as always. The value reported is the total kinetic energy of the envelope since only envelope has kinetic energy and the kinetic energy of gas is essential 0 in the first frame.

5.4.2 energy outside orbital radius

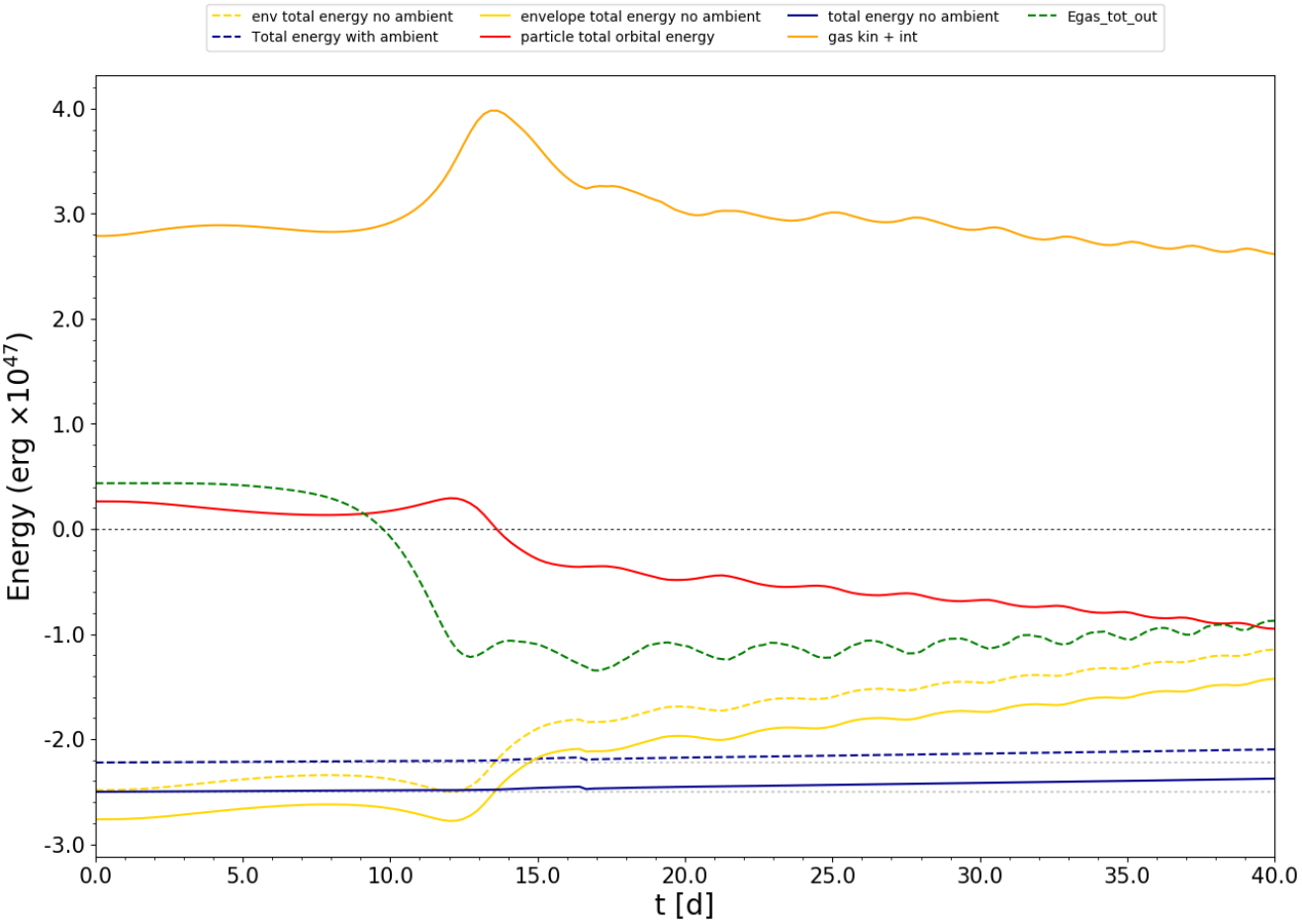


Figure 17: The energy of gas outside the orbit is denoted by the green line. The defination of outside is the compliment of "inside" defined above. The data recorded is not ambient removed. So I suggest compare across dashed line

The reason why I didn't remove the ambient is at the beginning, part of the ambient medium satisfies the definition of "outside". And it maybe misleading to simply subtract a certain value.

5.4.3 Energy flux through boundary

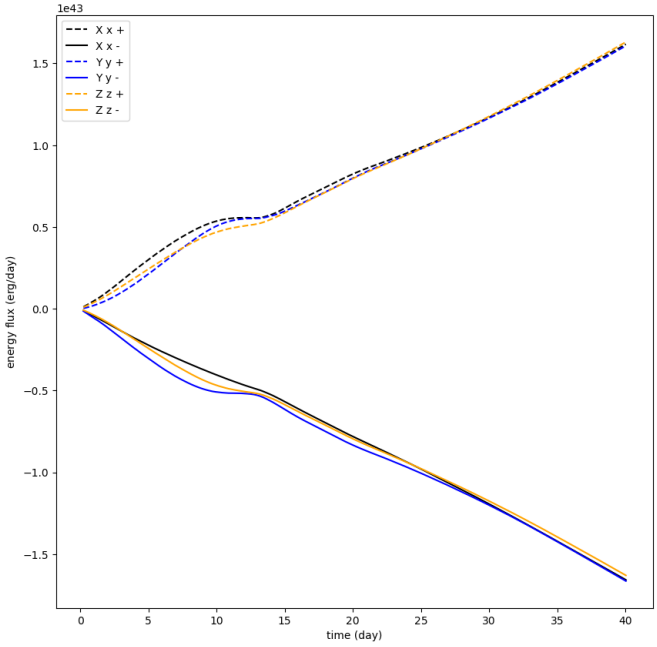


Figure 18: The energy flux through the boundaries. The notations are the same as the mass figure.

The energy plot looks nearly identical to the mass plot, meaning the mass getting into the box has similar energy throughout the simulation.
The cumulative energy inflow is $1.97 * 10^{45}$erg, which is less than the increase in total energy. The fraction it contributes is 9.75%.
Is it possible for all these entering mass have velocities directed to the center such that it impedes the ejection more?

5.5 Mass

5.5.1 Mass evolution

In this subsection we examine the mass evolution of the system

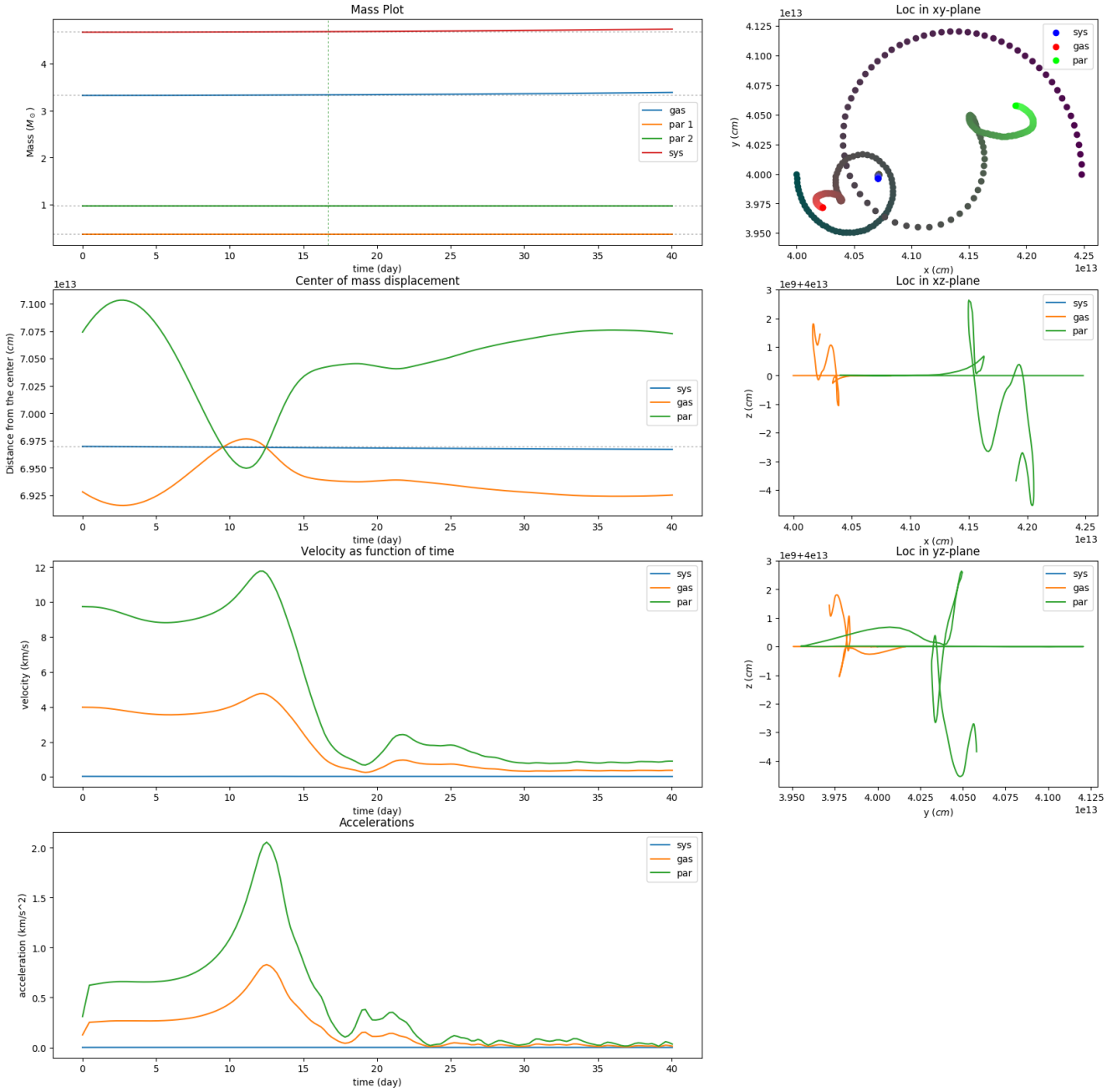


Figure 19: Mass evolution, the velocity and acceleration are scalars. They are the absolute value of the velocity/acceleration at that particular time

From the preceding figure, we can see that the total mass is relatively well-conserved. The initial mass is 4.66 $M_\odot$ and final mass is 4.73 $M_\odot$. The mass change fraction is $\frac{M_f - M_i}{M_i} = 1.38\%$. Counter-intuitively, the system is

actually gaining mass rather than losing mass, which explains why the system is gaining energy.
The total change in mass is equal to $0.06426 M_{\odot}$ over 40 days, which would require a mass change rate $0.0016 M_{\odot}$/ day on average, or $3.697 * 10^{25} g/s$

5.5.2 Unbound Mass

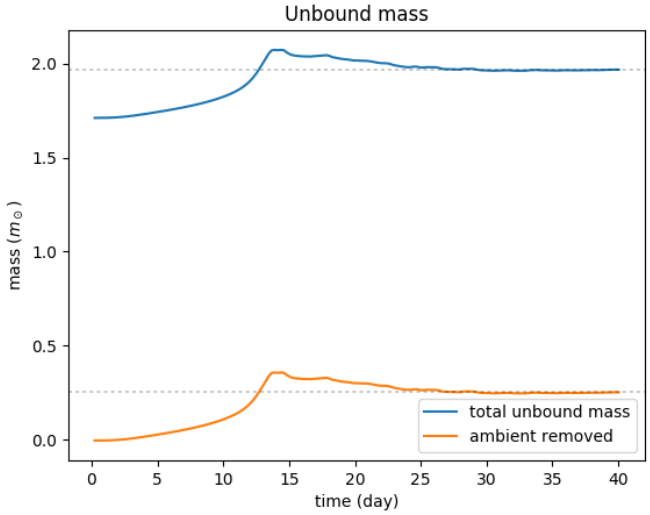


Figure 20: Amount of unbounded mass as a function of time

From the figure, it appears that the amount of mass unbound is increasing and then level off. The final total unbound mass is $1.96 M_{\odot}$ (59.37% of gas + medium) and the final unbound envelope (removing ambient) is $0.25 M_{\odot}$ (15% of gas only). The maximum unbounded envelope is $0.35 M_{\odot}$. The maximum seems to be reached when the secondary orbit around the primary exactly once (frame 57, 58 or 59, see appendix)
It appears that from this figure not much mass in the end gets unbound. Probably because most energy was taken away by some mass that was scattered at the beginning of the evolution. This would require further analysis on the distribution of mass and cross check with the energy plots.

5.5.3 Radial mass distribution

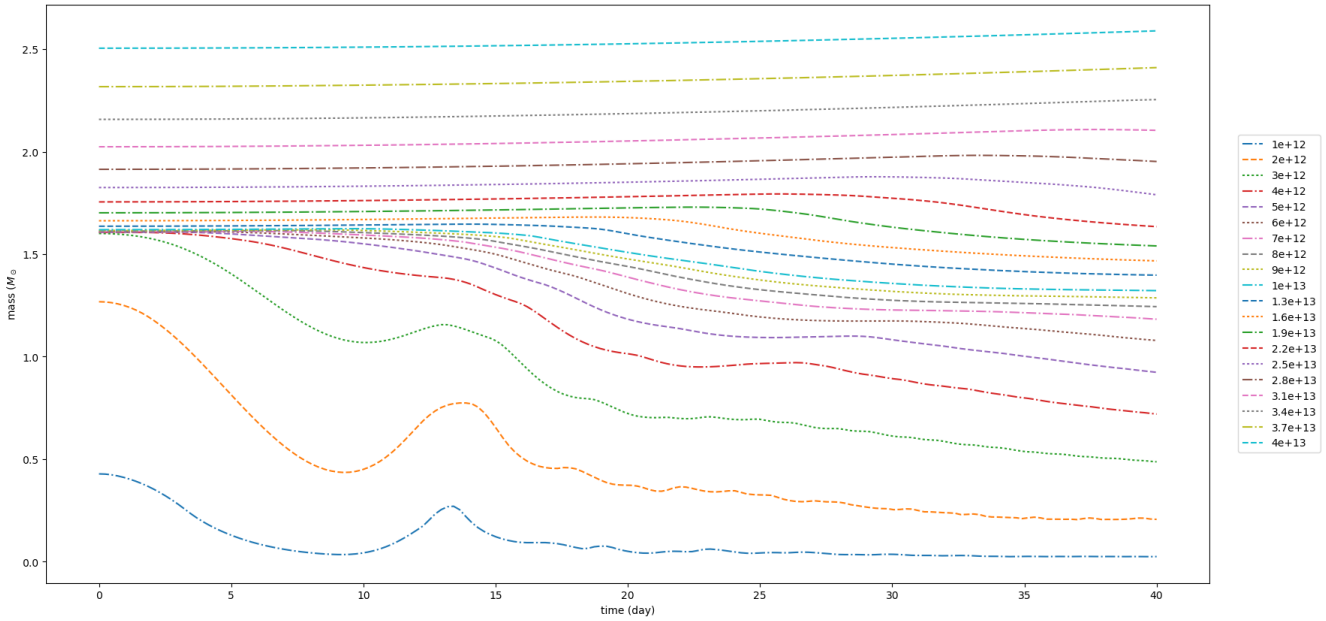


Figure 21: plot of mass inside a certain radius. The lines are cumulative so outer radius are further. The 10th line, the light blue line in the middle marks the transition between radius differ by 1e12 and by 3e12

In this figure, it appears that mass is transferring from the central region to the more outer regions. It looks like the mass was first concentrated inside radius $3 * 10^{12}$cm, which is expected because it's inside the RG. Later it transported to a region between $8 * 10^{12}$cm and $2.5 * 10^{13}$cm. However, it is interesting to notice that the top-most line is actually increasing. The top-most line denotes the ball exactly fit in the box. This increase meaning that there are material in-flowing into this boundary, part of which maybe due to inflow from boundary. It is likely that, if simulation were run longer, that the mass become concentrated around the middle region ($8 * 10^{12}$cm and $2.5 * 10^{13}$cm).

Luke said that there are inflow at the middle of the boundaries and outflow at the corners. It maybe worth to check these. It appears that this is true because the upper most curve here clearly changes more than the previous total mass curve.

5.5.4 Mass flux through boundary

To find the mass flux through the boundary, we use the following equation

$$\Phi_m = \int \rho_m v_m dA \tag{35}$$

where ρ_m is the density of mass at the boundary, v_m is the velocity of mass at the boundary and dA is the amount of area that a certain amount of mass pass through.
It should be noted that we are using simulation, meaning our dA is the area of a side of the grid. The method to perform this calculation is still developing, however it maybe logical to believe that the boundary grid is uniformally distributed. This subsection will require further investigation on the validity of the data, but I believe so far all logic sounds.
The process is used to find area of each mesh grid (dA)
Assuming that the grid are uniformally distributed so that each grid cell contribute to the total area for the same amount, then we can use the total area over the amount of cells on that level to get the area for each cell.

$$A_e = \frac{A_{\text{tot}}}{N} = \frac{(8 * 10^{13})^2}{262144} = 2.44 * 10^{22}\text{cm}^2 \tag{36}$$

And we multiply this to all values obtained from VISiT
I am not sure this process is actually necessary.

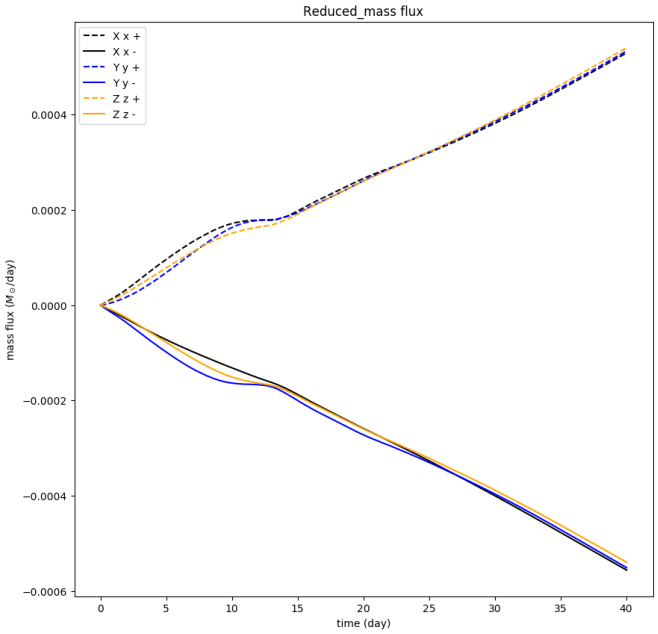


Figure 22: The mass flux through each edge in units g/s. Capital letters denote the plane, lower case letters and the + or - denote the 'positive' direction of velocity (into the box). i.e. if the flux is positive at +, it is coming into the box, or if the flux is negative at -, it is also coming into the box

Note that in this figure three of the cures are negative. That is because the material is traveling in the negative direction. However, because they are at the maximum end of axis, the material is actually coming into the box.
It appears from this figure that the amount of mass getting into the box is actually increasing. An approximation for calculating all mass coming into the box is by assuming that for all time between two frames, the rate is the same as the preceding frame. Then, the value would be $\Delta M_{\text{tot}} = 1.28 * 10^{32} g \approx 0.064 M_\odot$

5.6 Mass and particle orbit

5.6.1 Mass inside particle orbit

In this section we examine the mass within the particle orbit. A first approach is define "inside orbit" as a sphere centered at particle 1 and radius as separation between particle 1 and particle 2.

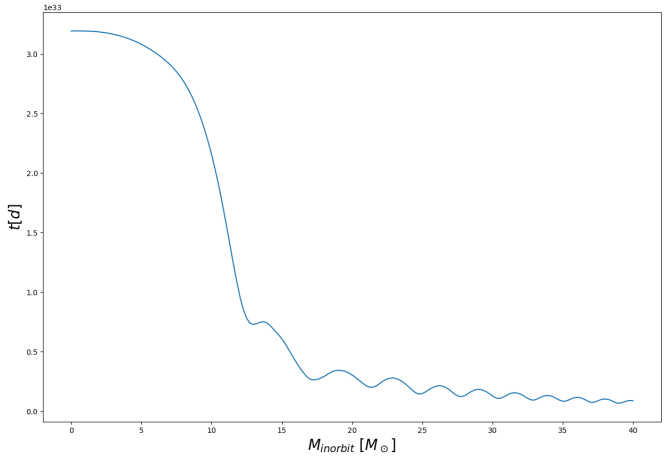


Figure 23: inside define as a sphere centered at particle 1 and radius as separation between particle 1 and particle 2

The final mass in orbit oscillates between order of magnitude 31 and 32 (about 1.3e32 to about 7e31).. The initial mass within orbit is $1.606 M_\odot$. Most of the mass are ejected in the process..
It appears that even excluding these mass, there is still too much mass to be ejected ..

5.6.2 Mass outside particle orbit

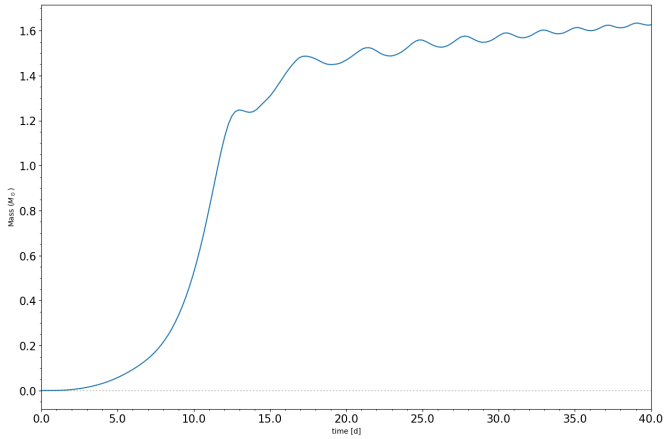


Figure 24: Mass outside the radius of the particle. The definition of outside is the compliment of the definition of inside. The value reported is ambient removed - every value is subtracted by 1.717 $M_\odot$.

From this figure, it appears that most of the mass is outside the orbit.. The final mass outside the orbit is $1.63 M_\odot$. The increase in mass can be explained by mass inflow (see previous section)

5.7 Momentum

5.7.1 Some Theoretical calculations

The momentum of a point mass is given by

$$\overrightarrow{p} = m\overrightarrow{v} \tag{37}$$

Or, in classical system, momentum can also be obtained from kinetic energy

$$|\overrightarrow{p}| = \sqrt{2mT} \tag{38}$$

Using this equation and the well-calculated kinetic energy from the first frame, we get the magnitude of momentum is equal to

$$|p_1| = 2.608 * 10^{39} \qquad \text{and} \qquad |p_2| = 1.386 * 10^{40} \tag{39}$$

The momentum of gas can be estimated by the preceding equation, but because gas don't move in the same direction and momentum doesn't distribute uniformly throughout the box, we can expect some deviation from the approximation. If the momentum calculated is similar to this value, meaning gas is moving at roughly the same direction; If otherwise, gas are moving mostly in opposite direction. Here, the calculation uses data from the second frame since the momentum in the first frame is 0 (all gas are stationary)

$$|p_g| = 1.639 * 10^{40} \tag{40}$$

Given the fact that the boundary flux of mass and energy is relatively close to each other on each side, we can expect that total momentum to be relatively conserved.
Angular momentum for a point mass is given by

$$\overrightarrow{L} = \overrightarrow{r} \times \overrightarrow{p} \tag{41}$$

The values reported are result of this calculation, with

$$\begin{aligned} L_x &= yp_z - zp_y \\ L_y &= zp_x - xp_z \\ L_z &= xp_y - yp_x \end{aligned} \tag{42}$$

where p_x, p_y, p_z are the three components of the momentum.
The initial position of the primary core (particle 1) is at the center. By defining the center of the box as the origin ($< 4 * 10^{13}, 4 * 10^{13}, 4 * 10^{13} >$). The initial angular momentum of the primary core should be 0. The location of the secondary is at $49R_\odot \approx 3.4 * 10^{12}$cm. Therefore we expect the initial angular momentum of the secondary to be $4.712 * 10^{52}$.
The final kinetic energy of particle 1, particle 2 and gas is given by

$$T_{p1} = 5.90 * 10^{46}\text{erg} \qquad , T_{p2} = 2.02 * 10^{46}\text{erg} \qquad T_{gas} = 4.20 * 10^{46}\text{erg} \tag{43}$$

Using the formula above and accounting for the effect of boundary inflow, the expected absolute values of momentum are

$$|p_{f-p1}| = 9.31 * 10^{39} \qquad |p_{f-p2}| = 8.87 * 10^{39} \qquad |p_{f-gas}| = 2.38 * 10^{40} \tag{44}$$

The units for momentum are all in g cm/s

5.7.2 Momentum evolution

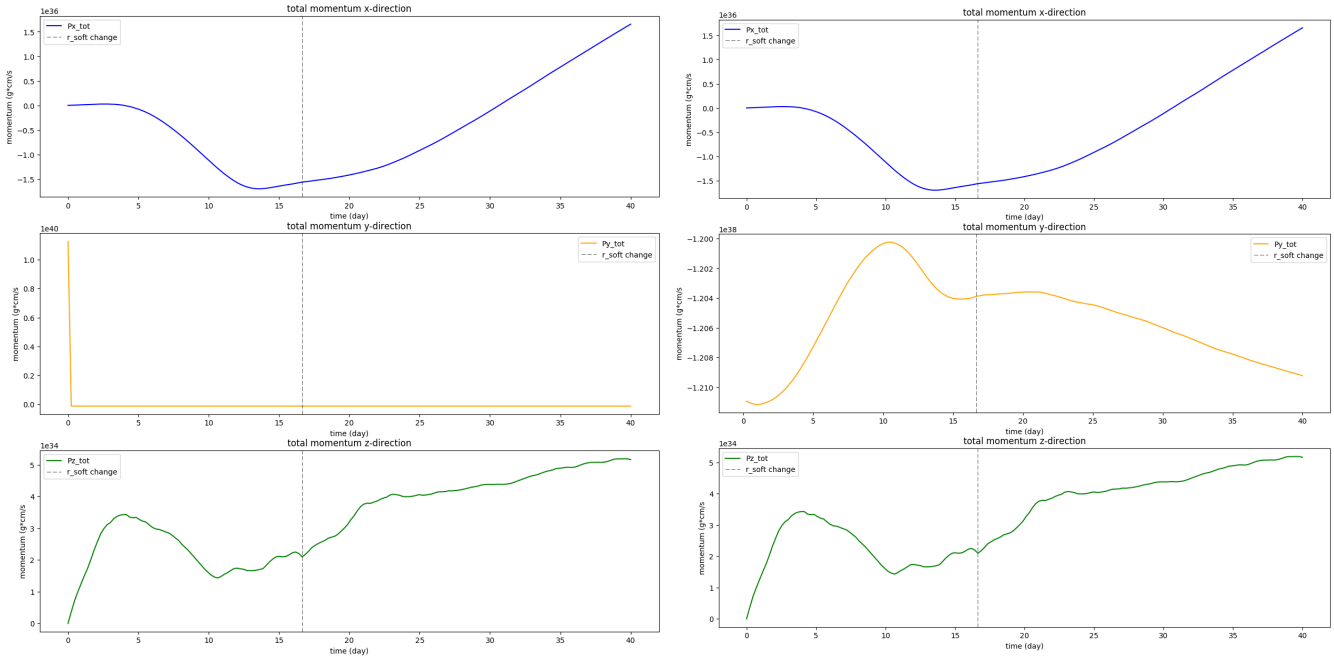


Figure 25: Left is original momentum data in each direction with all data kept; right is original momentum data with the first data of y removed so we can see more clearly the evolution of y. The vertical black dashed line denotes the softening length change time

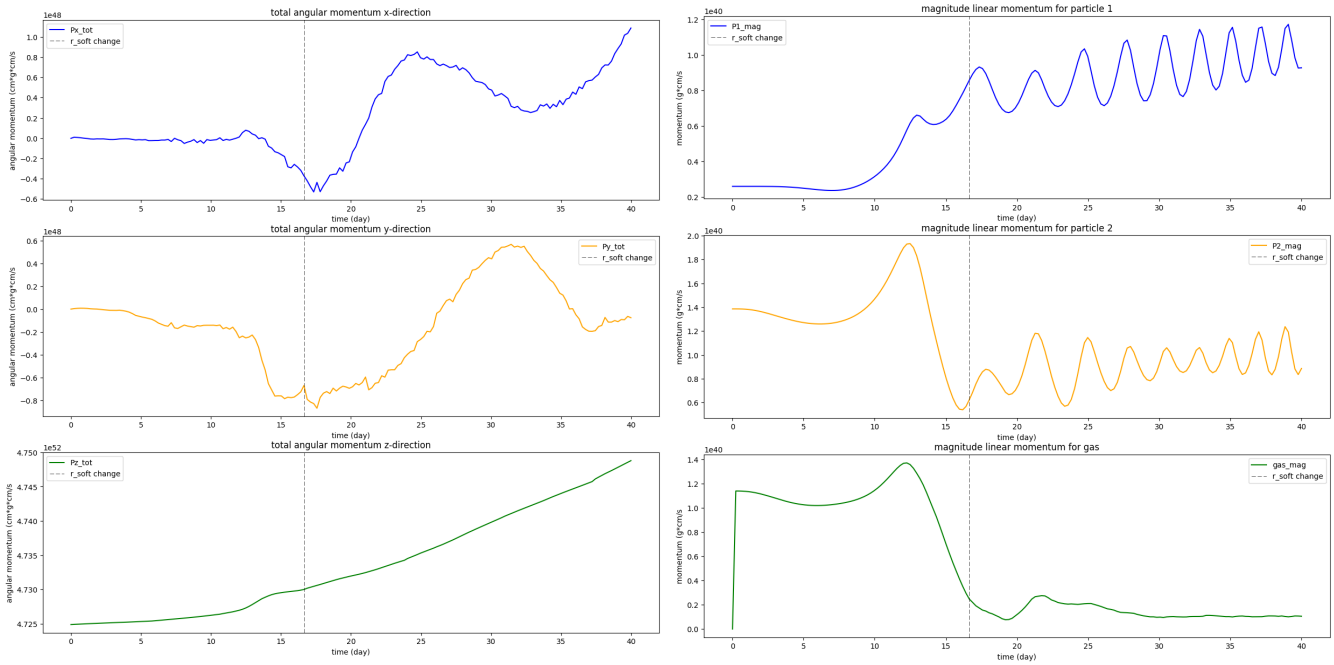


Figure 26: Left panel is total angular momentum in each direction. Right panel is the magnitude of linear momentum for particle 1, 2 and gas. The vertical black dashed line denotes the softening length change time

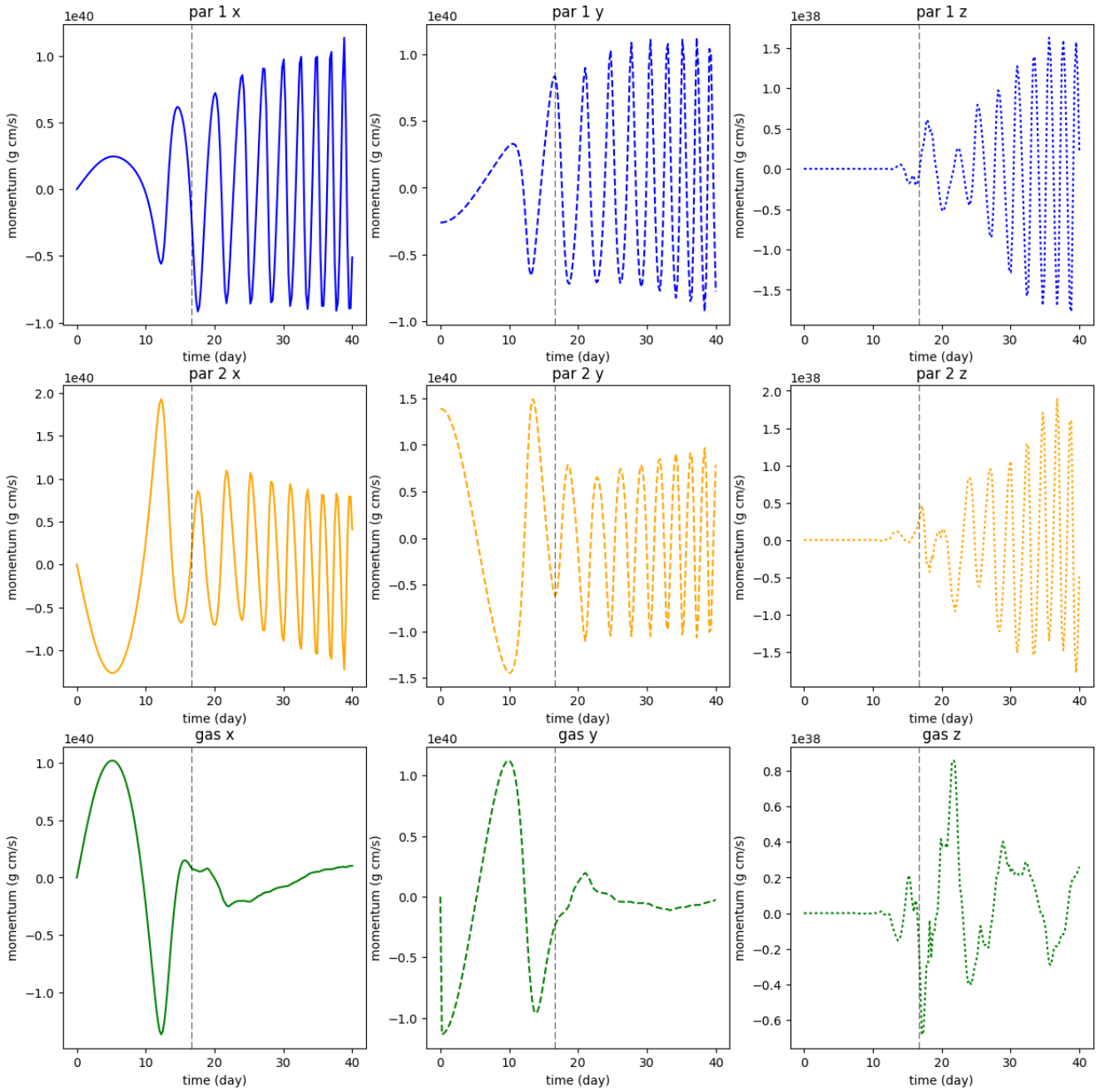


Figure 27: The components of particle 1, 2 and gas linear momentum. The black dashed vertical line denotes where the softening radius change. Same color means same mass component (gas, particle), same line style means same direction.

As checked, the initial linear and angular momentum for p1, p2 and gas, the final linear momentum for p1 and p2 all agrees with theoretical value. The final linear momentum of gas is smaller than calculated, which is expected and allowed since momentum in opposite direction cancels out each other whereas kinetic energy adds up.

It's been noted that there is a sudden jump in momentum in y direction. To estimate the correlation between momentum and energy, we calculate the difference between the absolute values of momentum in y direction in

frame 0 and 1. For particles and gas, the result is following

$$\Delta|p_{gas}| = 1.136 * 10^{40} \qquad \Delta|p_{p1}| = -4.67 * 10^{36} \qquad \Delta|p_{p2}| = -2.77 * 10^{37} \tag{45}$$

If we estimate the kinetic energy change corresponding to each component using $\Delta T = \frac{\Delta p^2}{2m}$, we get

$$\Delta T_{gas} \to 9.79 * 10^{45}\text{erg} \qquad \Delta T_{p1} \to 1.49 * 10^{40}\text{erg} \qquad \Delta T_{p2} \to 1.97 * 10^{41}\text{erg} \tag{46}$$

And the total change in kinetic energy is

$$\Delta T_{tot} \to 9.79 * 10^{45}\text{erg} \tag{47}$$

The actual change in kinetic energy between frame 0 and 1 is $2.037 * 10^{46}$erg, which is about twice of this value. However, they are roughly on the same order of magnitude. Given the fact that momentum can cancel due to direction but kinetic energy adds up, this explains (mostly) the change in kinetic energy. In this case, it appears that most gas suddenly moves in the negative y-direction without effecting the cores too much. Need further study between 0 and 1 frame

Since momentum is not conserved, it would be necessary to look at the boundary momentum flux.

The oscillation pattern agrees with the separation vs time plot in [1]. The decrease pattern for gas momentum in figure 26 right bottom panel agrees with the patterns in figure 19 gas center of mass velocity pattern

5.7.3 Momentum flux through boundary

The equation to obtain momentum flux is simply $p_{\mathbf{j}} * v_{\mathbf{r}}$ where j denotes momentum direction and r is the unit vector perpendicular to the surface. Then sum this value over one edge of the box.
It is interesting to notice when two vectors parallel to each other entering from either sides of the box with velocity opposite each other, the values obtained will be exactly the same for these two vector. So we need to subtract one from the other to get the flux we want. For each edge, there are three components of momentum coming into the box, so there are 18 values to consider.
The reported total momentum flux for x axis through the two parallel edges is calculated by

$$\Phi_{px} = (\Phi_{px,x0} - \Phi_{px,x1}) + (\Phi_{px,y0} - \Phi_{px,y1}) + (\Phi_{px,z0} - \Phi_{px,z1}) \tag{48}$$

where px denotes the x direction momentum, $x0$, $y0$, $z0$ denote edges corresponding to surface at $x = 0$, $y = 0$, $z = 0$ ("The lower edge") and $x1$, $y1$, $z1$ denote edges corrosponding to surfaces at $x = 8 * 10^{13}$, $y = 8 * 10^{13}$, $z = 8 * 10^{13}$ ("The upper edge").

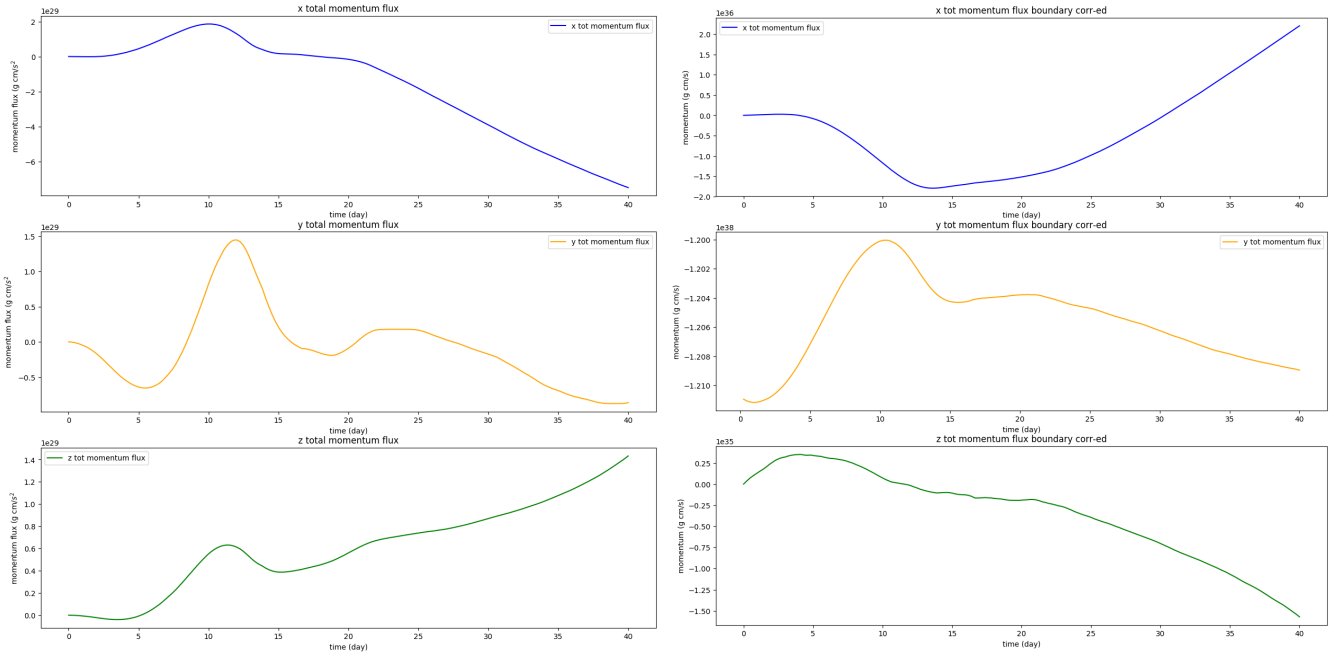


Figure 28: Left panel is momentum flux through boundary in each direction. Right panel is total momentum in each direction in each frame accounted for boundary flux. Note that in right panel center figure (corrected total momentum y direction), the first frame is removed. If added, it would be exactly the value provided above since culumative flux through the boundary in the first frame is 0

From the figures we see that flux in x direction seems to be negative, where as in z direction it seems to be positive. y direction the flux is changing signs rapidly.
The figures in the right panel doesn't look too different from the the previous ones. In fact, the order of magnitude for left panel is 10^{29}. If we times $2 * 10^5$, the time step between each frame, the order of magnitude is 10^{34}, which still cannot account for changes in order of magnitudes 10^{35}, 10^{36} or 10^{38}.
It appears that neither momentum or energy is conserved in this simulation, which makes me wonder what causes this. Could it be our solver is not perfect so there are slight deviation expected? Or time step issues? Or maybe it's some other numerical problem that wasn't picked up for now

6 Original data

6.1 Time dependence of energy

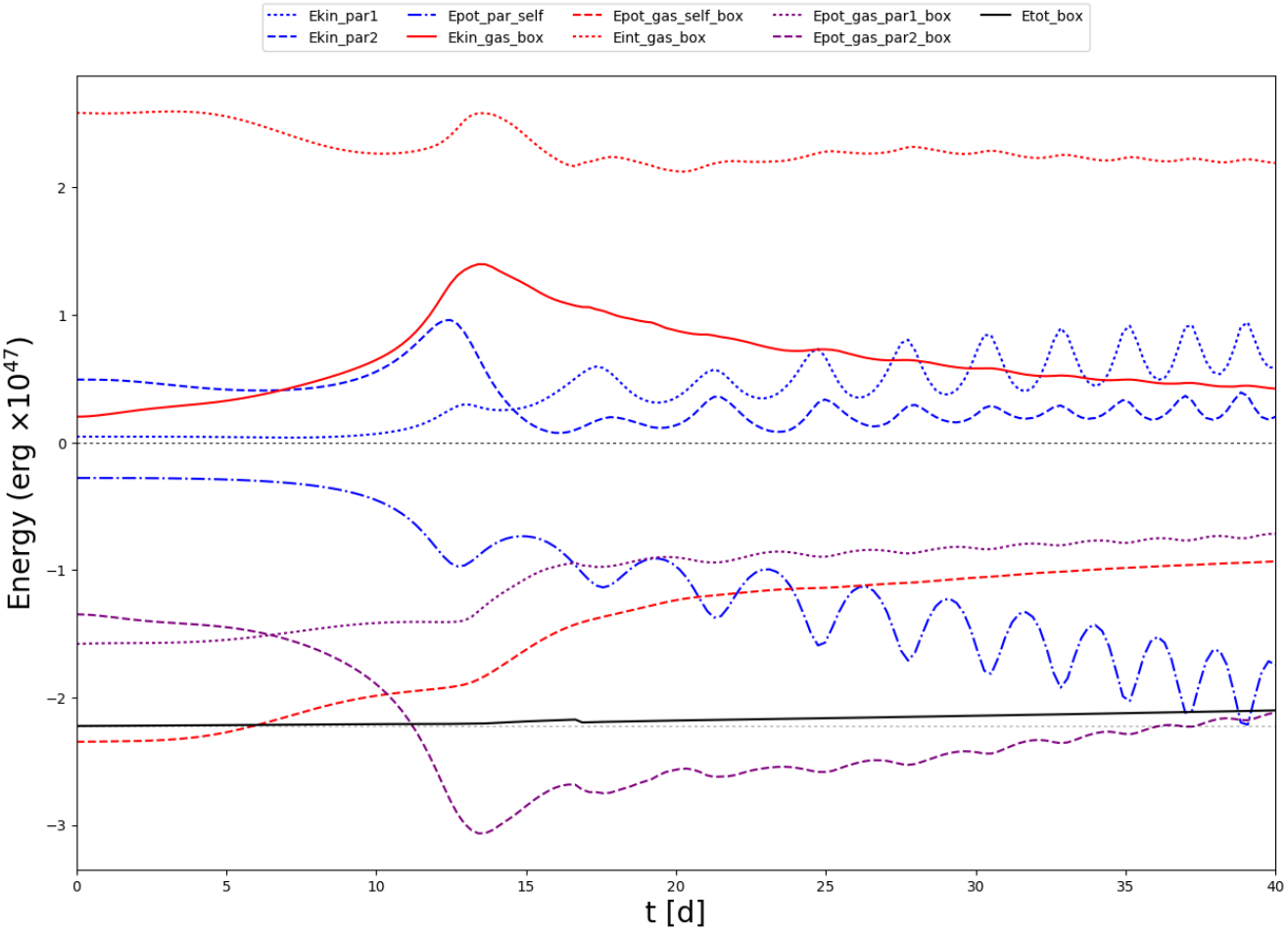


Figure 29: The figure is high resolution main energy plot. This figure is original data

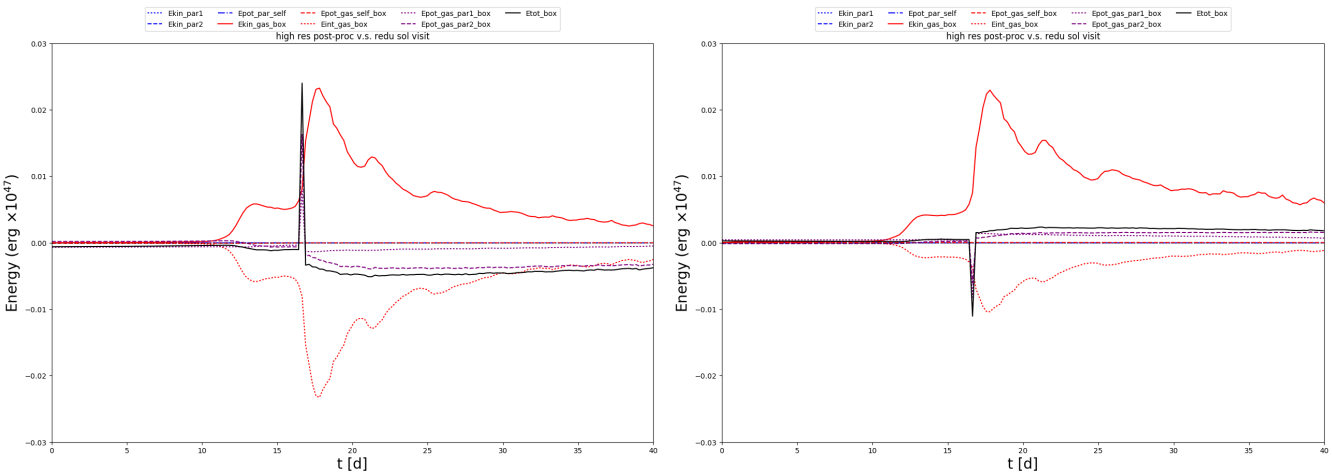


Figure 30: left: difference between high res and low res, value reported is $D143_{full} - D143_{redu}$; left, percentage difference, value reported is $(D143_{full} - D143_{redu})/D143_{full}$

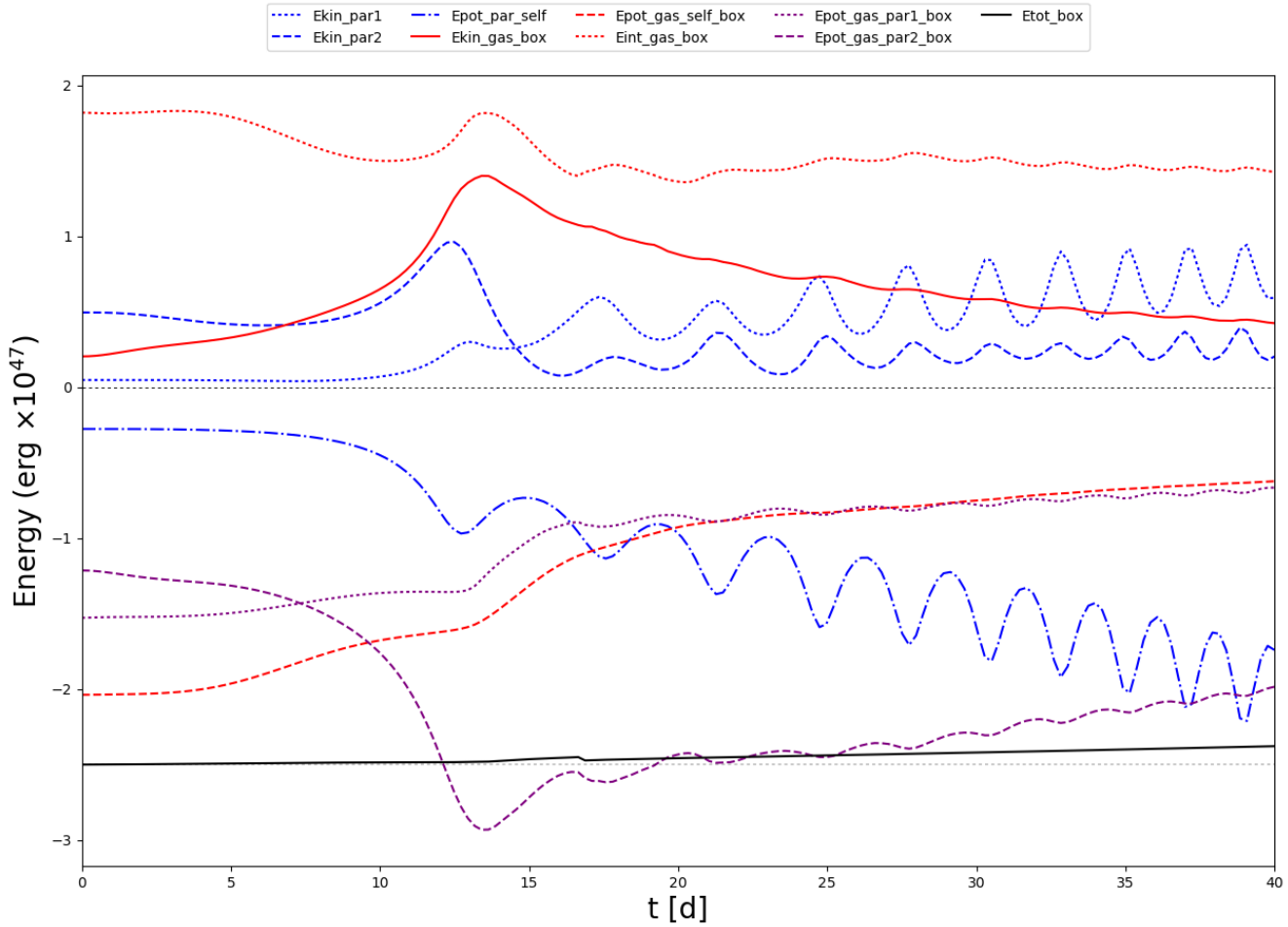


Figure 31: The figure is high resolution main energy plot. This figure is original data with ambient removed

Due to computation issue with VISIT, not all curves are generated using VISIT.
The quantities generated by VISIT is T_{par1}, T_{par2}, T_{gas}, $U_{gas-self}$, $U_{par1,par2}$, $E_{int,gas}$. Other two values, $U_{gas,par1}$ and $U_{gas,par2}$ are generates using post processing Damp_RGB_JC.
The comparison between reduced data and high resolution data is shown in figure 30. The values compared are the values used to generate the plots in this note. The value reported are $D_{highres} - D_{lowred}$, where D denotes any quantity.
Because the method to remove ambient medium is purely analytic, resolution would not change the parameter used to remove the ambient material.
figure 30. shows that the deviation is on order of magnitude 45. which is insignificant to values on order of magnitude 47. The value difference is 2%
The total change in energy is $1.22 * 10^{46}$erg, which is 5.49% of total energy change (recall reduced resoultion the difference is 5.92%)

6.2 Theory and simulation value comparison

6.2.1 Values comparison

Description	Semi-analytic	Simulation1 redu sol	simulation2 high sol	diff hi/S	note
Energy involving particle only					
Initial particle 1 kinetic energy	0.05	0.046	0.046	0.004	
Initial particle 2 kinetic energy	0.49	0.494	-0.494	-0.004	
Initial particle kinetic energy	0.54	0.540	0.540	0.0	
Initial inter-particle potential energy	-0.28	-0.278	-0.278	-0.002	
Final inter-particle potential energy	-1.95	-1.743	-1.743	-0.2069	(II)
Gas energy budget					
Initial envelope bulk kinetic energy	0.20	0.203	-0.203	-0.003	
Initial envelope internal energy	1.81	1.817	-1.817	-0.0069	(I)
Initial envelope particle 1 potential energy	-1.56	-1.529	-1.529	-0.031	(I)
		-1.529	*CHANGE*	CHANGE	*(VI)*(VIII)
		-1.547	CHANGE	CHANGE	(VII)(VIII)
Initial envelope particle 2 potential energy	-1.21	-1.216	-1.216	-0.006	(I)
		-1.216	*CHANGE*	CHANGE	*(VI)*
		-1.216	CHANGE	CHANGE	(VII)
Env-par2 pot energy if par 2 at RG center	-4.14				
Initial envelope potential energy, self gravity	-2.13	-2.039		○	(I)
Initial ambient medium internal energy	0.77 (0.768)	0.768		✓	(V)
Initial ambient medium-particle 1 pot energy	-0.05 (-0.0497)	-0.025	-0.025	-0.0243	(III)
Initial ambient medium-particle 2 pot energy	-0.13 (-0.138*)	-0.066	-0.066	-0.072	(III)
Initial ambient medium envelope potential energy	-0.22 (-0.215)	???			
Initial ambient medium pot energy, self-grav	-0.09 (-0.0922)	-2.34			
Initial gas-particle 1 potential energy					
Initial gas-particle 2 potential energy					
Initial gas pot energy due to self-grav					
Initial envelope binding energy (< 0 = bound)					
RG core-env PE only	-1.56	-1.529	-1.529	-0.0310	(I)
		-1.529	*-0.031*		*(VI)*
		-1.547	-0.013		(VII)
RG core-env PE + intern	0.25	0.289	0.288	-0.0389	(I)
RG core-env PE + Env-env PE + intern	-1.87	-1.750	-1.751	-0.119	
RG core-env PE + intern + env bulk KE	0.46	0.492	-0.491	-0.0319	
RG core-env PE + Env-env PE + intern + env bulk KE	-1.67	-1.548	-1.548	-0.1219	(I)
RG core-env PE + Sec-env PE	-2.77	-2.744	-2.745	-0.025	(I)
RG core-env PE + Sec-env PE + Env-env PE	-4.90	-4.784	-4.784	-0.116	(I)
RG core-env PE + Sec-env PE + intern	-0.96	-0.926	-0.927	-0.0339	(I)
RG core-env PE + Sec-env PE + intern + env bulk KE	-0.76	-0.724	-0.725	-0.035	(I)
RG core-env PE + sec-env PE + Env-env PE + intern	-3.09	-2.966	-2.967	-0.123	
ANS + env bulk KE	-2.89	-2.763	-2.764	-0.126	
As above but with secondary at center of RG	-5.82	N/A			
Liberated from change in orbital energy					
Ivanova et al. (2013) eq (3) RHS					
Initial orbital energy	-0.75	-1.494	-1.494	0.744	(IV)
Final orbital energy	-0.97	-1.743	-1.743	0.773	(IV)
Initial orbital energy of particle only	-0.14	-0.278	-0.278	0.138	(IV)
By particles only	0.83	1.465	1.465	-0.6350	(IV)

6.2.2 Explanations for disagreements

I) The simulation values are calculated using the data from simulation and subtract the value in parenthesis in Semi-analytic column. The calculation of these values are in Energy note.

II) The difference in r_{final} caused the problem. The particles are in elliptical orbits, and it's hard to define a r_{final} for elliptical orbit

III) The simulation calue reported cut areas within radius $3.35 * 10^{12}$, whereas in calculation all areas are included. This is a calculation independent of other calculations.

IV) They are differ by about a factor of two because the simulation value didn't account for kinetic energy. However, for final orbital energy, the particle is in elliptical orbit, so Virial Theorem doesn't work in this case (not a factor of 2)

V) This value is actually term E in chombo file. Because we know E_kin in the first frame is 0 in the file (disregard our correction), $E = E_{int}$

VI) This value is computed directly using VisIT. A function called is 'clip'. I cut out all regions beyond $3.35 * 10^{12}$cm, and calculated the potential energy due to the gas left. This value considers the spline potential. (Calculated using de-resolved data)

VII) This value use the same method as previous one. This value did NOT consider the spline potential (Calculated using de-resolved data).

VIII) It turned out that the mass inside the sphere is smaller than we expected (By VisIT, the mass inside sphere $r = 3.35 * 10^{12}$ is $1.606 M_{\odot}$. The theoretical value is $1.597 M_{\odot}$. Since in Theory, a larger mass would result in a potential tnat is more negative, the distribution of mass may not be the same as we believed. A task maybe possible would be calculating the mass distribution and comparing with our template.

6.3 Spacial dependence of energy (TO BE DONE)

6.3.1 Normalized energy figures (TO BE DONE)

6.3.2 Radial Energy distribution (TO BE DONE)

6.3.3 Energy flux through boundary

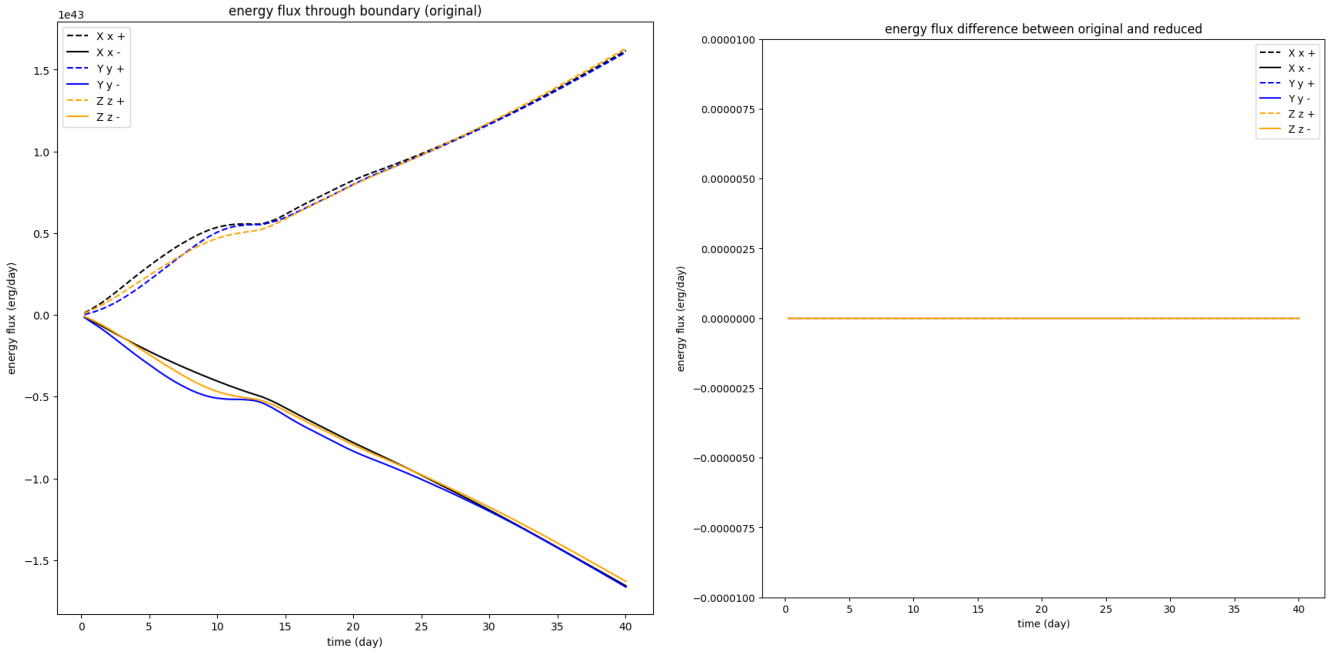


Figure 32: Left panel: Energy flux through boundary. Right panel: the difference between original and reduced resolution data

It turned out that boundary energy flux is exactly the same for these two runs.

6.4 Mass (TO BE DONE)

6.4.1 Mass evolution

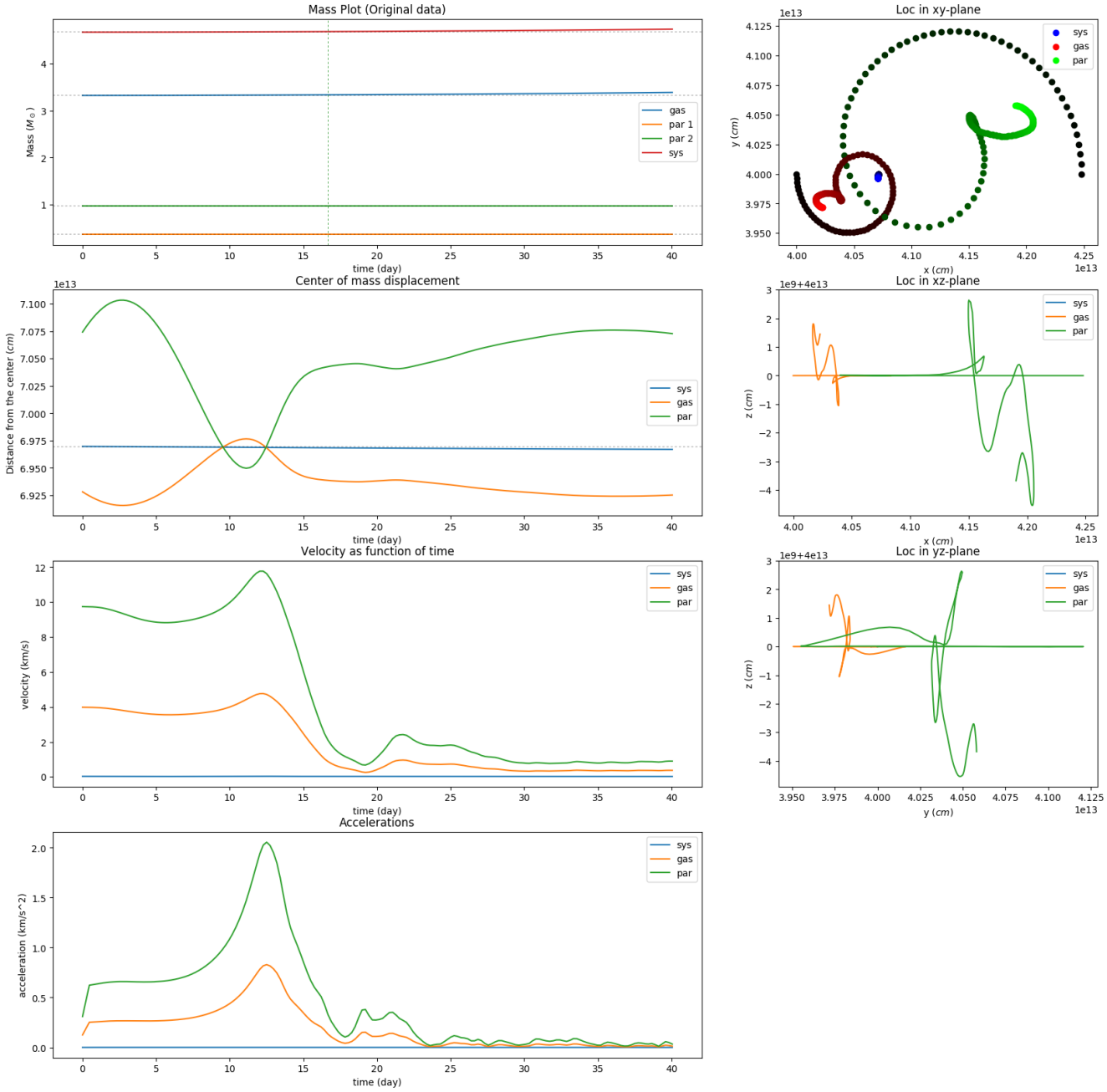


Figure 33: The figure with data from the original data set.

The mass evolution of the original data seems also relatively well. The system initial mass is $4.66M_\odot$, final mass is $4.73M_\odot$. This data is extremely similar to that of the reduced resolution. The deviation is less than $1.7 * 10^{-6}\%$ for initial mass and 0% (No deviation at all) for final mass.
The mass change is $0.064M_\odot$, which is 1.4% of the original mass. This data is again very similar to that in the reduced resolution one.

The final velocity of the particle center of mass is 0.899km/s. And the final acceleration of the particle CM is 0.033km/s^2
It is interesting to notice that the initial mass of the gas obtained from calculation is different from that obtained from the python file. The deviation is about $0.018M_\odot$
The data here was double-checked.

6.4.2 Unbound Mass (TO BE DONE)

6.4.3 Radial mass distribution (TO BE DONE)

6.4.4 Mass flux through boundary

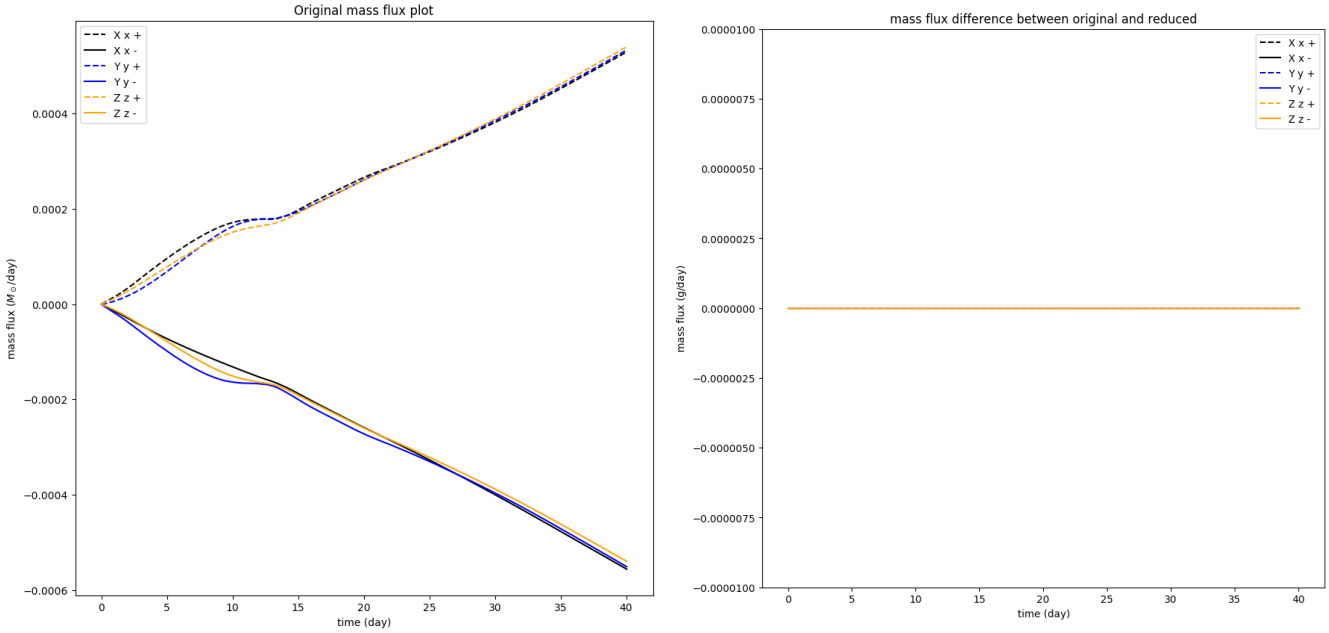


Figure 34: Left: mass flux into the box. Note that because this plot preserves the sign of velocity, the negative values actually come into the box. Right: difference between mass flux in each frame.

It turned out that there are no difference between reduced resolution data and original data.
Interestingly I was getting the conclusion that there is a 0.03% difference, which left me wondering if I made a mistake somewhere in the script or I should be a little bit skeptical about the computer results with large numbers. Either way, I will double check the result. I checked the original data and they appears to be exactly the same when I looked at some values randomly.

6.5 Mass and particle orbit (TO BE DONE)

6.5.1 Mass inside particle orbit (TO BE DONE)

6.5.2 Mass outside particle orbit (TO BE DONE)

6.6 Momentum

6.6.1 Momentum evolution (TO BE DONE)

6.7 Momentum flux through boundary (TO BE DONE)

7 Ideas

7.1 Roche Lobe Overflow

During binary star interaction, a phase that usually meet by people is the Roche Lobe Overflow. In this phase, material from one star get transported onto the other.
The idea here is whether Roche Lobe Overflow phase can bring extra energy to the ejection of common envelope. Most of the energy in this phase comes from the decay of orbital energy. (Assuming that such overflow doesn't drive fusion). Then we need to consider the energy released from the beginning of Roche Lobe Overflow to when the star plunge in.
When two stars reach Roche Lobe overflow, according to Eggleton [3], the radius of the red giant r_1 and the distance between the star A is given by

$$\frac{r_1}{A} = \frac{0.49 * q^{\frac{2}{3}}}{0.6 * q^{\frac{2}{3}} + \ln\left(1 + q^{\frac{1}{3}}\right)} \tag{49}$$

where $q = \frac{m_1}{m_2}$
Now, if we plug in the numbers from our simulation (Table 1), then we get

$$r_{roche} = A = 7.73737 * 10^{12}\text{cm} = 111.248 R_\odot \tag{50}$$

Consider the system evolves from this radius to the plunge in radius ($r_{in} = 49 R_\odot$), by assuming that the secondary reach "stable" orbit on each radius, we can estimate the energy by applying the Virial Theorem

$$E_{orb,Roche} = -G\frac{M_{rg}M_2}{2r_{in}} - \left(-G\frac{M_{rg}M_2}{2r_{roche}}\right) = -4.16507 * 10^{46}\text{erg} \tag{51}$$

If all these energy is transported into envelope, then the energy is about 2/3 of the energy required
A flaw of logic in this argument maybe there are mass transfer and mass lose in the process of the evolution.
I am not sure if the following is correct.. The overflow system can be a chaotic system that is hard to be modeled. The transfer rate is approximated by Paczy nski, B., Sienkiewicz, (1972). The simulation in macleod's paper has a really different value than ours and it's actually hard to tell how the system will behave if it finally reaches a system like ours..
We also need to take into account that because there are mass lose, the remaining energy may not be as large as we estimated. Some of the gas maybe ejected with high energies that takes away a lot of energy (need grounds for this argument).

References

[1] Luke Chamandy, Adam Frank, Eric G. Blackman, Jonathan Carrol-Nellenback, Baowei Liu, Yisheng Tu, Jason Nordhaus, Zhuo Chen and Bo Peng *Accretion in common envelope evolution.* MNRAS 000, 000-000(0000)

[2] Sebastian T. Ohlmann, Friedricj K. Röpke, Rüdiger Pakmor and Volker Springel *Hydrodynamic moving-mesh simulation of the common envelope phase in binary stellar systems.* The Astrophysical Journal Letters, 816:L9 (6pp), 2016 January 1

[3] Eggleton, P. P. *Approximations to the radii of Roche lobes.* The Astrophysical Journal. 268: 368. Bibcode:1983ApJ.268.368E

[4] Paczy nski, B., Sienkiewicz, R. *Evolution of close binaries.* 1972, AcA, 22, 73

[5] Andreas Büning and Hans Ritter *Numerical stability of mass transfer driven by Roche lobe overflow in close binaries.* Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D–85741 Garching, Germany

[6] Seidov Skvirsky 2000 *Gravitational potential and energy of homogeneous rectangular parallelepiped.* PACS numbers: 01.55.+b, 45.20.Dd, 96.35.Fs

[7] H *H.* H

8 Appendix

8.1 Appendix A: equation for figures

Ekin_par_tot = Ekin_par1 + Ekin_par2
Ekin_tot = Ekin_par2 + Ekin_par1 + Ekin_gas_box
Epot_tot = Epot_gas_par2_box + Epot_gas_par1_box + Epot_gas_box + Epot_par
Etot_env = Ekin_gas_box + Epot_gas_box + Eint_gas_box + Epot_gas_par1_box
Epar_tot = Ekin_par1 + Ekin_par2 + Epot_par + Epot_gas_par2_box

Epot_tot_no_self = Epot_gas_par2_box + Epot_gas_par1_box + Epot_par
Etot_env_no_self = Ekin_gas_box + Eint_gas_box + Epot_gas_par1_box + Epot_gas_par2_box
Updated: 07/22/2018 08:03 PM

8.2 Appendix B: A more clean-up plot

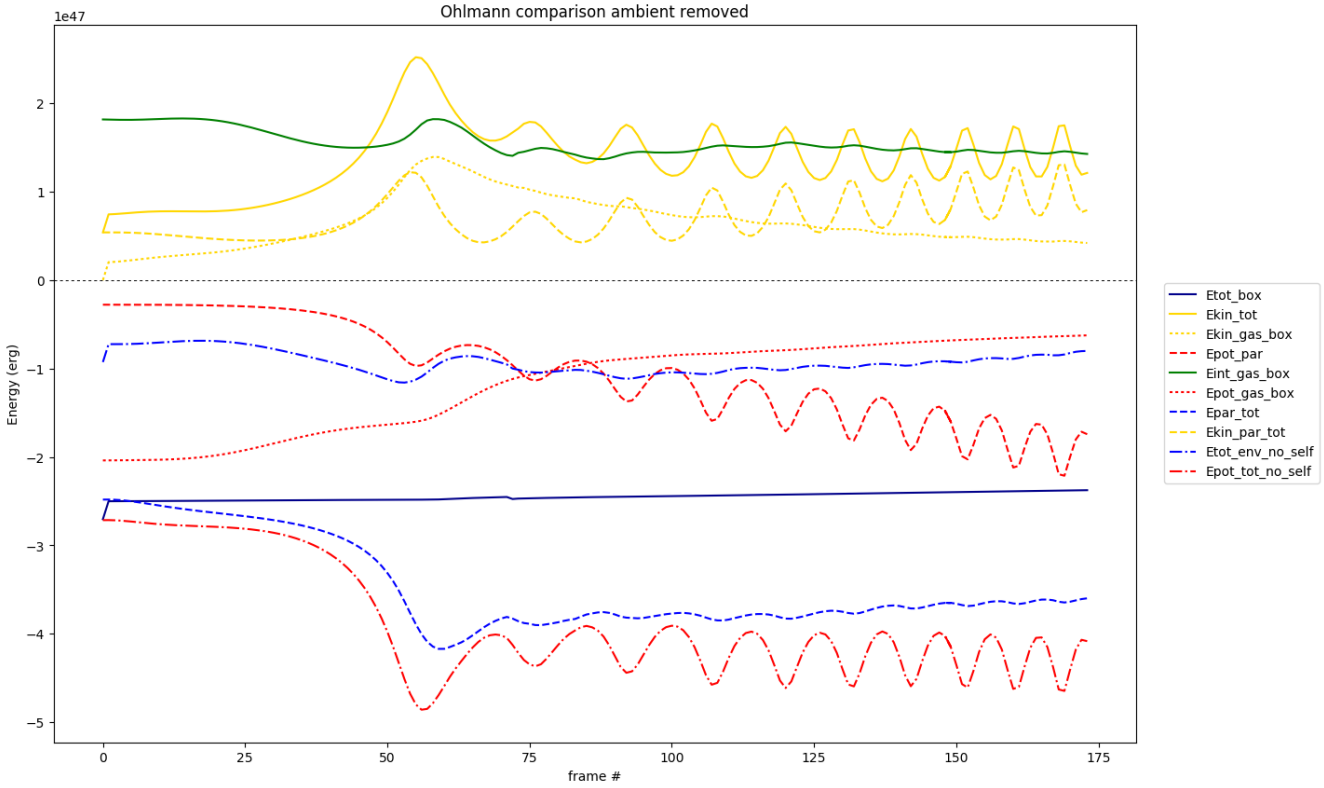


Figure 35: A more cleaned up plot of figure 2

8.3 Appendix C: supplementary: some other figures

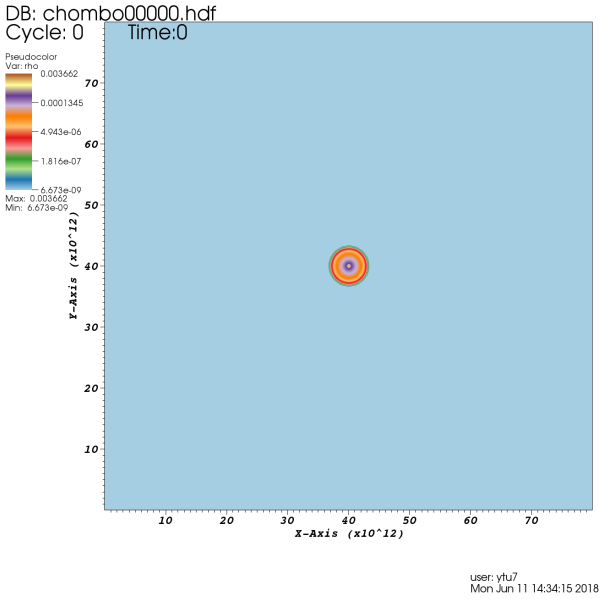


Figure 36: Density, frame 0, cut from z-axis

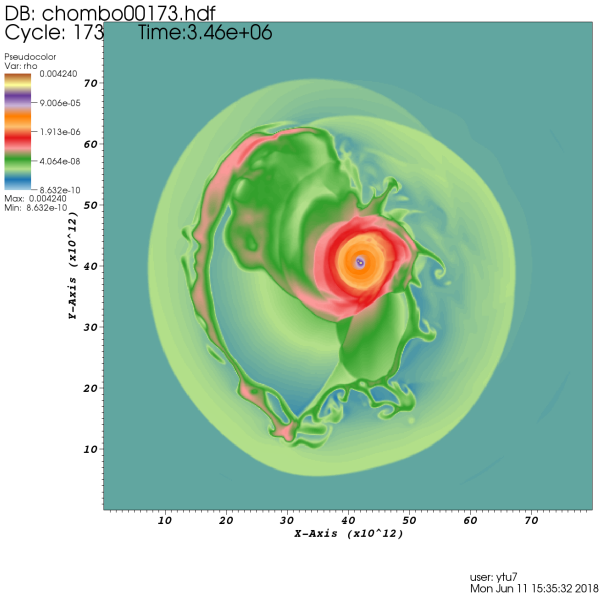


Figure 37: Density, frame last, cut from z-axis

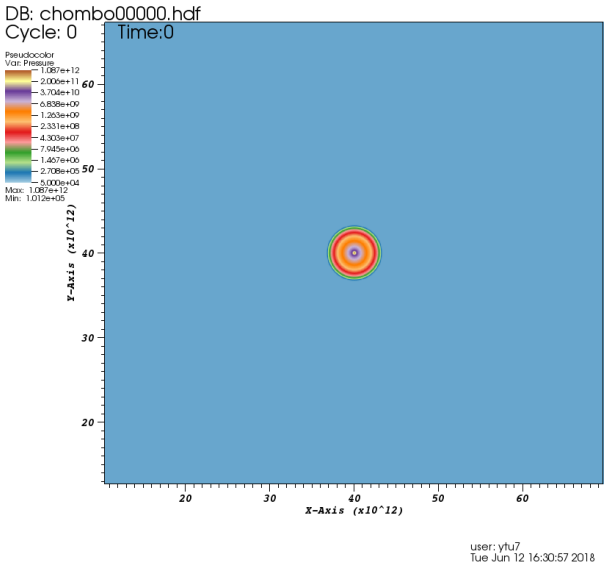


Figure 38: Pressure, frame 0, cut from z-axis

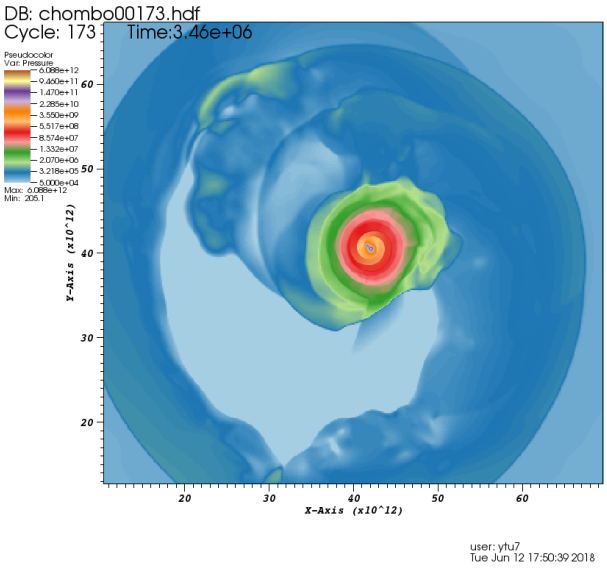


Figure 39: Pressure, frame last, cut from z-axis

8.4 Appendix D: Energy and Mass distribution frame 57-59 (includes E_{gg}