# Modelling the Effects of Star Formation with a Volumetric Feedback Model

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# ABSTRACT

We implemented two new models (an original and a revised) for star formation and supernova feedback into the astrophysical hydrodynamics code Enzo. These models are designed to efficiently capture the bulk properties of galaxies and the influence of the circumgalactic medium (CGM). Unlike Enzo's existing models, these do not track stellar populations over time with computationally expensive particle objects. Instead, supernova explosions immediately follow stellar birth and their feedback is deposited in a within a predefined volume of cells. Our models were tested using simulations of Milky Way-like isolated galaxies, and we found that neither model was able to produce a realistic, metal-enriched CGM. Our work suggests that volumetric feedback models are not sufficient replacements for particle-based star formation and feedback models.

### **1** INTRODUCTION

The large-scale structure of the universe is dominated by dark matter and its resulting gravitational potential, and individual galaxies are no exception. A galaxy's baryonic components, its stars, gas, and dust, sit within the potential well of its accompanying dark matter halo. While the baryons emit all the light we observe from galaxies, galaxy masses are dominated by the dark matter. Stars form near the center of the halo, where the gravitational potential is the strongest. In a spiral galaxy like our Milky Way, which has a mass of roughly  $10^{12}$  M<sub> $\odot$ </sub>, most stars and their interstellar medium form a disk structure because of their angular momentum. Away from the center of the dark matter halo, the baryon density is too low to form stars. Instead, there exists the diffuse, multiphase gas of the circumgalactic medium (CGM). Despite its low density, the CGM is estimated to contain roughly half of the galaxy's total baryons [Tumlinson et al. 2017; Werk et al. 2014]. It is also believed to substantially impact the bulk properties of the galaxy, such as its star formation history [Voit et al. 2015a].

While galaxies evolve over time, at a given age of the universe they are observed to follow strong scaling relations. Properties such as luminosity and metallicity<sup>1</sup> are highly correlated to the mass of galaxy's dark matter halo [Graves et al. 2009; McConnachie 2012; McGaugh 2005]. These correlations imply galaxies self-regulate themselves to a state that depends primarily on the mass of the halo and its associated system.

The CGM is believed to be a key player in this process. One possible mechanism is that of "precipitation" [Voit et al. 2015a] in which CGM gas cools and falls deeper in to the potential well and onto the disk. This cold, dense infall encourages star formation. When massive stars (with mass greater than about  $8 \text{ M}\odot^2$ ) die, they explode as supernovae, ejecting energy and metal-enriched material into their surroundings. This ejecta is known as feedback, as it strongly effects the galaxy as a whole. According to the theory of precipitation, feedback from stellar populations lowers the density of the CGM by pushing gas to larger radii. This in turn increases the timescale on which the gas will cool. Once the cooling timescale exceeds the gas' freefall timescale by a factor of ~ 10 [Voit and Donahue 2015; Voit et al. 2015b,c], cold gas is no longer able to precipitate and cause further star formation. This decreased ability to form stars is known as "quenching."

We would like to examine the plausibility of this theory using numerical simulations; however, current simulations of single galaxies cannot resolve the scales on which individual star formation occurs. Star formation cannot be directly modeled in a galactic context, as we lack the computational resources needed to efficiently resolve the wide range of spatial and temporal scales that separate star formation and overall galactic dynamics. Instead, the effects of star formation and feedback can be modeled with heuristic "subgrid" models. If galaxy self-regulation by precipitation is to be considered a plausible explanation for galaxy behavior, galaxy models should be robust to the exact model of star formation and feedback chosen. These models, which involve tracking particles throughout the simulation, also add a good deal of computational expense. Some effects of precipitation, such as the reproduction of the mass-metallicity relation predicted in [Voit et al. 2015a], only affect the bulk properties of the galaxy. In this case it would be preferable to have a simpler, more idealized model of star formation and feedback.

The development of such a model, with the goal of testing the scaling relations predicted in [Voit et al. 2015a], is the focus of this work. Our models were implemented within Enzo. This code, as well as its existing treatment of star formation and feedback using particles, is described in Section 2.1. As a computationally cheaper alternative to particles, we employ a volumetric approach to feedback, which is described in Section 2.2. Massive stars are assumed to immediately result in supernovae in order to avoid tracking their ages and masses, as the details of the stellar populations are not the focus of our queries. Two models were developed: an original model, and a revised model. These models are referred to as "volumetric" as

<sup>&</sup>lt;sup>1</sup>Astronomers refer to elements heavier than helium as "metals". "Metallicity" refers to the metal fraction of a gas, measured relative to the metal content of the sun.

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 $<sup>^2\</sup>mathrm{A}$  mass measured in solar masses  $\mathrm{M}_\odot$  is measured with respect to the mass of our sun.

they deposit stellar feedback within a predefined simulation volume. The revised model is an attempt to alter some undesired behaviors that were observed in the original model. Section 2.3 covers the details of our simulation initial conditions and parameter sets. Next, Section 3 covers the simulation behavior over time (3.1 and 3.2) including the effects of parameter variations. Ultimately, neither model behaved as desired; exactly how the models failed to meet the mark and possible reasons why are discussed in Section 4. As this work resulted from a student project, Section 4.1 is where the student's experiences and challenges are discussed. A summary and concluding remarks are offered in Section 5.

#### 2 METHODS

Before discussing the specific model employed in this work (Section 2.2), we first introduce the code base that is used for our simulations in Section 2.1. Then, in Section 2.3, the initial conditions and parameter variations are described.

Table 1 contains a list of all relevant simulation parameters. Those with a symbol listed are used elsewhere in this paper; those without are included for reference. A list of values indicates a parameter was varied between different simulation runs; see Table 2 for the exact combinations and more details about the runs.

#### 2.1 Enzo

The models discussed in Section 2.2 below were implemented in Enzo [Bryan et al. 2014]<sup>3</sup>, a multi-physics hydrodynamics code designed to simulate astrophysical problems from cosmology to plasma turbulence. Enzo stores data as either particles or Cartesian grid cells. For grid data, Enzo employs adaptive mesh refinement (AMR) to balance accuracy and computational efficiency by improving grid resolution in user-defined areas of interest. An Enzo user may define these areas using a variety of criteria, such as baryon or dark matter density, the presence of shocks, or a geometric region. At the core of Enzo's physics are gravity and Eulerian (magneto)hydrodynamics. Gravity acts on both particle and grid cell data. For ordinary hydrodynamics, which is of interest to this work, there are two solvers: the ZEUS finite difference method (adapted from [Stone and Norman 1992]) and the finite-volume piecewise-parabolic method (PPM) [Colella and Woodward 1984].

Other important physics in Enzo includes radiation transport, star formation and feedback, primordial chemistry, and radiative cooling. Support for the latter two is provided by the GRACKLE library [Smith et al. 2017]<sup>4</sup>. Natively, star formation and feedback are modeled using particle objects instead of grid cells. These particles are not constrained to the grid where gas information is stored. Instead, they are free to move about the simulation volume. A single particle represents an entire stellar cluster. These particles track the mass distribution of stars in the cluster, as well as their lifetimes. All stars in the modeled cluster are assumed to form at the same time, but more massive stars live shorter lives. It is known from observations that stars with main-sequence mass  $\gtrsim 8 M_{\odot}$  die in supernova explosions, ejecting energy and metal-enriched material into the surrounding environment. This is referred to as feedback. In Enzo, feedback from a particle is deposited into the gas in nearby

Parameter Name	Symbol	Value
Halo Mass		$9\times 10^{11}~M_{\odot}$
NFW Concentration		12
Disk Gas Mass	$M_G$	$5 imes 10^{10}~{ m M}_{\odot}$
Disk Gas Temperature		$2 \times 10^5 \text{ K}$
Galaxy Radial Scale Height	rs	3.0 kpc
Galaxy Vertical Scale Height	$z_s$	0.4 kpc
Galaxy Extent (# of Scale Heights)	κ	4
Feedback Region Extent	$\kappa_{FB}$	[2, 3]
Star Formation Density Threshold	$\rho_{SF}$	$1 \text{ cm}^{-3}$
Feedback Density Threshold	$\rho_{FB}$	$0.01 \text{ cm}^{-3}$
Star Formation Temperature Thres.	$T_{SF}$	$10^{4.5}$ K
Feedback Temperature Threshold	$T_{FB}$	$10^{7} { m K}$
Star Formation Efficiency	$\epsilon_{SF}$	0.01
Star Formation Timescale	$\tau_{SF}$	10 Myr
Stellar Mass Removal Factor	η	[1, 100]
Energy SNe Feedback Efficiency	$\epsilon_{FB}$	$10^{-5}$
Mass SNe Feedback Efficiency	$\epsilon_{FB,M}$	0.25
Metal SNe Feedback Efficiency	$\epsilon_{FB,Z}$	0.02
Kinetic Fraction	$f_k$	[0, 0.25,
		0.5, 0.75, 1]
Returned Mass Fraction	$\eta_M$	0.25
<b>Returned Metal Fraction</b>	$\eta_Z$	0.2

Table 1: Relevant simulation parameters. Parameters accompanied by a symbol are used elsewhere in this work. Values in brackets correspond to simulation variations; see Table 2.

grid cells. Several different star formation and feedback models are available, which define when particles are created and the mechanism by which feedback is deposited into the surrounding grid cells.

#### 2.2 Volumetric Feedback Models

In our model, star formation and feedback can only occur within a cylinder of user-defined height and radius. This cylindrical region is located at the center of the domain, and encompasses the central region of the initial galactic disk. Within this domain, grid cells are flagged as being either star-forming or feedback-only depending on their density and temperature. If a cell has density  $\rho > \rho_{SF}$  and temperature  $T < T_{SF}$ , where  $\rho_{SF}$  and  $T_{SF}$  are parameters, it is flagged as a star-forming cell. If a cell has  $\rho_{FB} < \rho < \rho_{SF}$  and  $T < T_{FB}$ , where  $\rho_{FB}$  and  $T_{FB}$  are parameters, it is flagged as feedback-only. These two categories are constructed to be mutually exclusive, and most cells are not flagged at all. The temperature parameters should be set such that  $T_{FB} > TSF$ . The parameter  $T_{FB}$  also controls the energy budget for feedback (see Section 2.2.2).

Figure 1 shows what this flagging looks like for the density and temperature thresholds in Table 1. The grayscale shows a face-on density slice through the midplane of the disk. Overlaid in cyan and yellow are the star-forming and feedback-only cells, respectively. The red circle indicates the boundary of the star formation and feedback region. The scale bar corresponds to the radius of this region.

<sup>&</sup>lt;sup>3</sup>http://enzo-project.org/

<sup>&</sup>lt;sup>4</sup>https://grackle.readthedocs.org/



Figure 1: Density slice showing an example of star-forming (cyan) and feedback-only (yellow) cells within the feedback region (red circle; scale bar). The slice shows the galactic disk face-on, and passes through the midplane.

In the subsections below, we describe how star formation (2.2.1) and feedback (2.2.2) are handled with reference to these cell types. For each process, we first describe the treatment of the original model. Problems with the results of the original model (see the end of Section 3.1.1 and Section 4) induced some revisions which will be discussed later in each section.

2.2.1 Star Formation and Stellar Death. Once star-forming cells have been flagged, their total mass  $M_{SF}$  is used to calculate a mass of stars  $\Delta M_*$  formed during that time step  $\Delta t$  using the following formula:

$$\dot{M}_* = \epsilon_{SF} M_{SF} / \tau_{SF},\tag{1}$$

$$\Delta M_* = \eta \dot{M}_* \Delta t. \tag{2}$$

The star formation efficiency is  $\epsilon_{SF}$  and the formation timescale is  $\tau_{SF}$  (see Table 1). Stars are never directly modeled by either the original or revised schemes, because the goal of these models was to avoid the computational expense of explicitly including stellar populations via particles. Instead, only the effects of star formation on the surrounding gas are modeled:  $\Delta M_*$  worth of gas is removed from all star-forming cells. The amount removed from an individual cells is proportional to its fraction of the total star-forming cell mass  $M_{SF}$ .

The parameter  $\eta$  in Equation 2 allows mass to be removed from the simulation in excess of what is consumed by star formation. This mimics the ionization of surrounding gas that occurs when stars form, which prevents further star formation in the immediate area of the new stars. This removed mass is negligible compared to the mass of gas in the disk. Likewise, it has a negligible effect on the gravitaional potential, which is dominated by the dark matter and remaining gas. For the original model,  $\eta = 1$ . In the revised model,  $\eta$  is a tunable parameter (Table 1). When stellar populations in Enzo are modeled with particles, these particles keep track of the age and individual masses of their constituents. For simplicity in these models, stellar death is treated as though it immediately follows stellar birth. Not all stars are massive enough to result in supernova explosions; the efficiency parameters  $\epsilon_{FB}$ ,  $\epsilon_{FB,Z}$  and  $\epsilon_{FB,M}$  are chosen to reflect the fraction that do (see Table 1). The energy, mass, and metal returned by these supernovae is calculated in bulk:

$$\Delta E = \epsilon_{FB} \Delta M_* c^2,$$
  

$$\Delta M = \epsilon_{FB,Z} \Delta M_*,$$
  

$$\Delta Z = \epsilon_{FB,M} \Delta M_*.$$
(3)

For each time step,  $\Delta E$ ,  $\Delta M$ , and  $\Delta Z$  are added to "reservoirs" from which feedback energy and material are drawn. These reservoirs are maintained throughout the simulation, allowing past star formation to have some affect on current feedback.

2.2.2 Supernova Feedback. In these models, feedback constitutes the addition of energy, mass, and metal to a certain selection of cells, which we will refer to as "feedback cells." For the original model, feedback cells refer to the feedback-only cells discussed above in Section 2. In the revised model, feedback cells refer to *both* the star-forming and feedback-only cells. Unflagged cells do not receive feedback.

An "energy budget"  $e_b$  is calculated for each feedback cell. This is the amount of energy that would be needed for  $(1 - f_k)e_b$  to raise the temperature of the cell to  $T_{FB}$ , where  $f_k$  is the kinetic fraction. The interplay between this energy budget and the feedback algorithm will be discussed later. Recall from Section 2.2 that all flagged cells have  $T < T_{FB}$ . Feedback will only proceed if there are feedback cells to receive it, and if the sum of  $e_b$  for all the feedback cells is less than the amount of energy  $E_{res}$  in the energy reservoir.

For each cell, the energy budget is divided into thermal and kinetic energy based on the cell's height |z| from the galactic midplane. In the original model, every cell receives thermal energy  $e_t$  of exactly  $(1 - f_k)e_b$  (marked by a dashed line). Only the outermost layer of cells receives kinetic energy  $e_k = f_k e_b$ . For the revised model, the kinetic energy is given by  $e_k = f_k \tanh(2|z|/z_s)$  and the thermal energy is  $e_t = e_b - e_k$ . The thermal energy is never less than  $(1 - f_k)e_b$  (shown by the dashed line).

Mass and metal are also returned during feedback, and are proportional to the total amount of energy subtracted from the energy reservoir:

$$\Delta M_{ret} = \eta_M e_b / E_{res},\tag{4}$$

$$\Delta Z_{ret} = \eta_Z e_b / E_{res}. \tag{5}$$

This ensures that all three reservoirs - energy, mass, and metal - remain proportional to each other.

#### 2.3 Simulations

Our simulations are of a single, Milky Way-like disk galaxy. The galaxy is isolated in a  $(1 \text{ Mpc})^3$  box whose boundaries are periodic for baryons but not for gravity. The galactic disk is constructed as a cylinder of radius  $\kappa r_s$  and height  $\kappa z_s$  (see Table 1 for symbol definitions; the values chosen for  $r_s$  and  $z_s$  are consistent with Kim et al. [2016]) placed in a Navarro-Frenk-White, or NFW, dark matter halo (Navarro et al. [1996]; see Table 1). The disk's initial temperature is



Figure 2: Radial profiles of the simulation initial conditions. Top is density, middle is temperature, and bottom is entropy (the adiabatic invariant; see text). Profiles are measured from the center of the galaxy and extend out to 250 kpc (kiloparsecs). They show the average value at that radius.

uniform, while its density follows the double-exponential profile used in the AGORA simulation suite [Kim et al. 2016]:

$$\rho(x, y, z) = \frac{M_G}{4\pi r_s^2 z_s} e^{-r/r_s} e^{-|z|/z_s}.$$
(6)

Surrounding the disk is gas that follows the cored entropy profile  $K(r) = 4 + 20(r/100 \text{ kpc})^{1.15}$  [Voit et al. 2017]. This profile is used in conjunction with the assumption of hydrostatic equilibrium to calculate the density and temperature profiles for the CGM. As used here, "entropy" refers to the adiabatic invariant  $K = T/\rho^{\gamma-1} \approx T/n_e^{2/3}$ , where  $n_e$  is the electron number density and the ratio of specific heats is  $\gamma = 5/3$ . See Figure 2 for radial profiles of the initial density, temperature, and entropy out to a radius of 250 kpc. In addition to the feedback models discussed above, we use Enzo's gravity and PPM hydrodynamic solver, as well as radiative cooling with the GRACKLE library [Smith et al. 2017].

Model	$f_k$	$\kappa_{FB}$	η
Original	0.5	2	1
	0	2	1
	0.25	2	1
	0.75	2	1
	1	2	1
	0.5	3	1
Revised	0.5	2	100

Table 2: Parameter variations; each line corresponds to a different simulation. The first set listed for each model is fiducial parameter set for that model.

In total, seven simulations were run: six using the original model and one using the revised model. A summary of the parameter variations can be found in Table 2. The parameter set listed next to the model name is the fiducial set for that model. The original fiducial simulation ran for 8 Gyr of simulation time. The other non-fiducial simulations were set to run for 5 Gyr; however, only the model  $f_k = 0.25$  reached this mark in a reasonable amount of time. All others were halted because the evolution slowed to the point where progress was minimal, with the simulation timesteps of less than one year. The timestep is constrained by the Courant-Freidrichs-Levy (CFL) condition for stability and accuracy (see Bryan et al. [2014], Section 9). Section 3.1.2 has more detail on where each run was stopped. The fiducial run of the revised model was stopped at 2 Gyr as it was not producing a more realistic galaxy than the original model (see sections 3.2 and 4).

#### **3 RESULTS**

The results of the fiducial runs for both models are discussed below. First, we detail the behavior of the original model for its fiducial run, and then discuss parameter variations. Then we discuss the behavior of the revised model's fiducial run. The parameters were not varied for the revised model, because reasonable parameter values did not affect the overall outcome of the simulations.

#### 3.1 Original Model

3.1.1 Fiducial Run. The time evolution of the star formation rate (SFR) for the original fiducial simulation is shown in Figure 3. Note that this plot has been smoothed (original in grey dots) for easier viewing using a Savitsky-Golay scheme with 4th order polynomials and a window of 8001 elements. Times of interest are labeled A–C. These times correspond to the images in Figures 4–6, which show projections of the edge-on disk and its inner CGM in four quantities (clockwise from upper left): density, temperature, metallicity, and radial velocity, with the latter three weighted by density. The projections are through a slab 40 kpc thick and 100 kpc on a side.

There is an initial burst of star formation seen in Figure 3 that is triggered by the initial conditions. After this burst, the rate of star formation drops before rising again. Point A (Figure 4) falls in this lull. Point B (Figure 5) corresponds to the peak of the SFR curve, just before the rate begins to slowly fall. The steady-state behavior of the system is sampled at Point C (Figure 6).



Figure 3: Star formation rate (SFR) over time for the original fiducial run. For easier viewing, the blue line has been smoothed with a Savitsky-Golay scheme; see text The dashed grey line underneath shows the original data. The vertical red lines labeled A–C are at 0.40, 1.84, and 7.00 Gyr, and correspond to Figures 4–6.

Figure 4 shows that at Point A (0.40 Gyr), the cold, dense disk is metal poor, and surrounded by a hot bubble that arose from earlier feedback. There is a large amount of material above and below the disk. Some of this is outflowing gas (coded red in the lower right of Figure 4). The larger outflows are disconnected from the disk, as this material was ejected during earlier times when the SFR and corresponding instantaneous feedback were higher. Newer, smaller outflows are seen closer to the disk; there is less gas being ejected because the SFR is lower. When one simultaneously considers the projections of temperature, metallicity, and radial velocity, infalls of cold, metal-rich gas can be seen at the edges of the largest outflows. This gas comes from even earlier stellar feedback injection. Both infall and outflow are of roughly the same projected metallicity and temperature.

At Point B (1.84 Gyr), we are at end of the peak in the SFR curve from Figure 3. We see from Figure 5 that the CGM has become hotter, but it's metallicity has not increased in the substantial time since Point A. The metallicity of the disk, however, is higher than at A. Highly collimated infalling gas can be seen directly above and below the gas, with bursts of outflowing material to the sides; however, the outflows have a smaller radial extent than in Figure 4.

By the time the simulation reaches Point C, it is is approximately in its steady-state with an SFR of  $\sim 18~M_{\odot}~\rm yr^1$ . This is a significantly higher SFR than we expect for a Milky Way-like galaxy. In Figure 6 we see that the disk is has been greatly enriched by metals, and while the CGM has been heated relatively uniformly at this point, it is unenriched. There are no more large-scale outflows, but there is still collimated infall. From Figure 3 we see that the SFR has been decreasing up to this Point; therefore, both the amount of feedback injected and, by extension, the amount of ejected material has also been decreasing. There is less older ejecta to fall back on to the

disk, and less star formation and feedback to drive newer outflows. Overall, activity in and around the galaxy is calming down.

Considering Figures 4–6 together, along with insights from examining the evolution over each of the 1 Myr time outputs, several trends emerge. The temperature of the CGM increases over time, as does the metallicity of the disk. The CGM also becomes hotter; however, its metallicity never changes. What is especially noticeable from examining the evolution of the simulation is that all of the material ejected from the disk eventually falls back onto the disk without becoming buoyant in the CGM. Therefore, the CGM remains metal poor, while the disk becomes highly enriched. The outflows are of a lower entropy than the surrounding CGM gas (this is visible in Figures 4–6 via the temperature). This entropy deficiency would explain the lack of buoyancy in the outflowing gas.

3.1.2 *Parameter Variations.* Five variations on the fiducial parameter set were run for the original model. In four of these runs, the fraction of total energy budget that went into kinetic energy  $(f_k)$  was varied. In the fifth, the kinetic fraction remained at the fiducial value of  $f_k = 0.5$ , while the size of the feedback region  $\kappa_{FB}$  was increased from 2 to 3 scale heights in both *z* and *r*.

Figure 7 shows how the star formation rate for all the parameter variations compares to the fiducial value (shown in thin grey dots; the same curve as Figure 3). These SFR curves have been smoothed in the same way as Figure 3, and have been limited to 5 Gyr for clarity. Values near  $f_k = 0.5$  (solid lines) did not produce much variation in the SFR curve. Extreme values (dash-dot lines), however, differ greatly from the fiducial run. The fully thermal feedback of the  $f_k = 0$  run constantly heated the gas in the disk, making it increasingly less able to form stars. Interestingly,  $f_k = 1$  maintains a steadier, if lower, SFR than any of the  $0 < f_k < 1$ . Lastly, increasing



Figure 4: Projections of the original fiducial run at 0.40 Gyr, centered on the edge-on disk and inner CGM. This figure corresponds to Point A in Figure 3. Clockwise from upper left: density; density-weighted temperature, density-weighted radial velocity, and density-weighted metallicity. Negative  $v_r$  is outward. The galaxy is actively producing metal-enriched outflows (red), and shows signs of earlier feedback (hot bubble, blue inflows). Each projection is 100 kpc wide and through a slab 40 kpc thick.

the extent of the feedback region,  $\kappa_{FB}$ , leads to an SFR curve with a similar shape to the fiducial run, but with a larger initial burst and stretched in time. This is a reasonable result, as increasing  $\kappa_{FB}$ increases the amount of gas that can form stars.

The  $f_k = 0.25$  simulation was able to run for the initially planned length of 5 Gyr, as was  $f_k = 1$  (neither was extended to 8 Gyr like the fiducial run). The run with  $f_k = 0.75$  was stopped after 1.8 Gyr because of its slow progress; because of the resulting high velocities, the simulation took very small time steps. Similarly, the  $f_k = 0$ simulation only ran for about 1 Gyr, as did  $\kappa_{FB} = 3$ . For the former, the elevated temperatures resulting from the completely thermal feedback greatly restricted the size of the time step that could be taken.

From Figure 7, it appears that any  $0 < f_k < 1$  will produce an SFR curve like Figure 3. The exact value has more of an impact on the evolution of the simulation than its behavior. Varying the size of the feedback region stretches the SFR curve but slows the simulation's evolution. Additionally, runs with  $f_k = 0.25$ ,  $f_k = 0.75$ , and  $\kappa_{FB} = 3$ 



Figure 5: Shows the same quantities as Figure 4, but for Point B of Figure 3 at 1.84 Gyr. The galaxy is at its peak star formation rate, yet there is more infalling gas (dark blue) from previous feedback than recent outflows (red). Both outflows and inflows are the only enriched gas.

reproduce the same overall behavior of the fiducial run: increasing metallicity in the disk but not the CGM, increasing temperature and density of the CGM (except the density for  $f_k = 0.25$ ), and all outflowing gas eventually falling back on to the disk.

#### 3.2 Revised Model

We will now consider the results of the revised feedback model. Like Figure 3, Figure 8 shows the star formation rate over time for the revised fiducial model. This model shows much less star formation overall, as expected: with this revised model, cold gas is being removed in excess of that used to form stars, diminishing the galaxy's gas reserves. This removal of extra gas is analogous to how cold, dense gas in stellar environments is destroyed by processes such as OB associations and Type II supernovae.

As before, times of interest are marked by red lines marked D and E, at 0.25 and 1.15 Gyr, respectively. Figure 9 corresponds to Point D, showing the simulation during the peak of a small star burst. Point E marks a quiescent period for the galaxy, and corresponds to Figure 10.

We see in Figures 9 and 10 that the metallicity of the disk increases over time, while that of the CGM remains constant. This is



Figure 6: Shows the same quantities as Figure 4, but for Point C of Figure 3 at 7.00 Gyr. The galaxy has achieved an approximate steady-state. Recent outflows (red) are small, and inflows (dark blue) are highly collimated; both are the only enriched gas.

the same behavior as seen in Section 3.1.1 with the original fiducial models. We also see that the temperature increases over time, as before. Unlike the original run, however, the density increases slightly around the disk.

From the radial velocity projections of both Figures 9 and 10, we see highly collimated material falling onto the galaxy. Just as with the original simulation, all the material that blows out from the disk eventually falls back in. Moreover, we again see that the outflows have a lower entropy than the surrounding CGM. The metal-rich outflowing gas does not become buoyant, and the CGM remains unenriched as with the original model.

This simulation was stopped before 5 Gyr, not because of slow progress, but because of insufficient difference from the original feedback model in terms of the CGM metallicity and outflow entropy. Additionally, there were also no variations in kinetic fraction  $f_k$  tested, because for  $0 < f_k < 1$ , the precise value had no effect on the evolution of the CGM (see Section 3.1.2; values of 0 and 1 for  $f_k$  do have an effect but are physically unrealistic).



Figure 7: Star formation rate (SFR) over time for parameter variations of the original model. The fiducial simulation (Figure 3) is shown as the thin grey dotted line. Extreme variations in the kinetic fraction  $f_k$  are shown as dash-dotted lines. Values near the fiducial  $f_k = 0.5$  are solid lines. The increase in feedback extent  $\kappa_{FB}$  is the thick dotted line. All curves have been smoothed using the same method and parameters as in Figure 3.

#### DISCUSSION 4

The aim of this work was to create an idealized, simplified model of star formation and feedback that does not have the same limitations as the standard particle-based star formation and feedback models typically used. Such a model was intended to explore how galaxies self-regulate themselves in a computationally efficient manner. We developed two models, an original model and a revised version, that emulated instantaneous star formation and feedback in a volumetric manner. The star formation rate of the original model was unrealistically high, which is partly why the revised model was developed. The revised model reduced the star formation rate through the removal of extra cold gas.

We see in Section 3, however, that these feedback models fail to produce realistic CGMs. A real CGM has metals [Tumlinson et al. 2017]. Both the original and revised feedback models (Sections 3.1 and 3.2) see a build-up of metal in the disk while their CGMs remain at the metallicity of the initial conditions. While the feedback is able to drive enriched outflows, this gas has insufficient entropy to achieve buoyancy in the CGM and instead falls back on to the disk. It's not entirely clear why the entropy of the ejected gas is so low. With these simulations, enough thermal energy is added to boost the temperature of the gas to 10<sup>7</sup> K, but the ejecta quickly fragments and cools. It may be that the gas is in a density and metallicity regime where it cools very efficiently, so that its entropy is always below that of the surrounding CGM. If metal enriched gas is not sufficiently hot, its cooling efficiency only increases as its



Figure 8: Star formation rate (SFR) over time for the revised fiducial run. Unlike in Figure 3, the blue line has not been smoothed. The vertical red lines labeled D and E are at 0.25 and 1.15 Gyr, and correspond to Figures 9 and 10.

temperature drops and runaway cooling occurs. The low entropy problem is also likely compounded by the continual heating of the CGM: the temperature difference between the ejecta and its surroundings is ever increasing, thereby making buoyancy an ever harder state for the ejecta to achieve.

Further reasonable modifications to the revised model would result in a method similar to an existing particle method, which is what this work was trying to avoid. The failure of both the original and revised models to produce a realistic, enriched CGM strongly suggests to us that a volumetric feedback scheme cannot replace a method that directly models stellar populations.

# 4.1 Student Challenges<sup>5</sup>

This was my first experience to both inheriting another person's code, as well as modifying an existing code base. As a result, the majority of my time at the beginning of this project was spent learning the internals of Enzo and logic of the method my predecessor had designed but never tested. As I stepped in to modifying Enzo for myself, I became much better at debugging and even had the occasion to use a memory profiler. Many of the error messages Enzo produces, as is often the case with a complex code, were symptoms of the underlying problems rather than directly related to the bug. This was how I was exposed to the many ways hydrodynamic solvers can fail, and how to mind Enzo's AMR hierarchy.

I presented this project at three academic conferences; once while it was in progress and twice when it was finished. Since this work took place during my final year of my Bachelor's degree, the experience gained from this project was a large component of my graduate school and fellowship applications. As of this writing I am a first-year graduate student with the Department of Energy Computational Science Graduate Fellowship. The work done as a part of this project has been tremendously helpful in preparing me for this fellowship.

# 5 SUMMARY

This work sought to create a volumetric model for star formation and feedback that was more computationally efficient than existing particle-based methods. Our goal was to use this model to explore how galaxies self-regulate themselves by examining the bulk properties of isolated galaxy simulations. Unfortunately, our volumetric feedback models failed to produce realistic galaxies:

- In our original model, the star formation rate was unrealistically high for a Milky Way-like galaxy.
- Additionally, the feedback failed to enrich the CGM with metals like in a real galaxy, because the ejecta did not become buoyant.
- The revised model fixed the SFR problem, but not the enrichment problem; ejecta still failed to become buoyant.
- Metal-enriched, ejected gas is likely cooling too efficiently to attain buoyancy.

Any further modifications we considered moved the models closer to the existing computationally-expensive particle methods we were trying to avoid. We therefore found that our volumetric models are not a plausible way of treating star formation and feedback in isolated galaxies. A different approach may still yield a model that avoids the expense of particles, and allow for the efficient examination of bulk galaxy properties.

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<sup>&</sup>lt;sup>5</sup>Written from the perspective of C. Kopenhafer.



Figure 9: Projections of the revised fiducial run, in the same quantities as Figure 4, but for Point D of Figure 8 at 0.25 Gyr. The galaxy is shown during an early burst of star formation, with part of an earlier metal-enriched outflow beginning to fall back on to the galaxy (blue).

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# REFERENCES

- Greg L. Bryan, Michael L. Norman, Brian W. O'Shea, Tom Abel, John H. Wise, Matthew J. Turk, Daniel R. Reynolds, David C. Collins, Peng Wang, Samuel W. Skillman, Britton Smith, Robert P. Harkness, James Bordner, Ji-hoon Kim, Michael Kuhlen, Hao Xu, Nathan Goldbaum, Cameron Hummels, Alexei G. Kritsuk, Elizabeth Tasker, Stephen Skory, Christine M. Simpson, Oliver Hahn, Jeffrey S. Oishi, Geoffrey C. So, Fen Zhao, Renyue Cen, and Yuan Li. 2014. ENZO: An Adaptive Mesh Refinement Code for Astrophysics. *The Astrophysical Journal Supplement, Volume 211, Issue 2, article id. 19, 52 pp. (2014).* 211 (apr 2014), 19. https://doi.org/10.1088/0067-0049/211/2/19
- P. Colella and Paul R. Woodward. 1984. The Piecewise Parabolic Method (PPM) for Gas-Dynamical Simulations. *Journal of Computational Physics (ISSN 0021-9991), vol. 54, April 1984, p. 174-201.* 54 (sep 1984), 174–201. https://doi.org/10.1016/0021-9991(84) 90143-8



Figure 10: Same quantities as Figure 9, but for Point E of Figure 8 at 1.15 Gyr. The galaxy is in a quiescent period with no large-scale outflows; however, there are highly collimated inflows of enriched gas (dark blue).

- Genevieve J. Graves, S. M. Faber, and Ricardo P. Schiavon. 2009. Dissecting the Red Sequence. I. Star-Formation Histories of Quiescent Galaxies: The Color-Magnitude versus the Color-σ Relation. *The Astrophysical Journal, Volume 693, Issue 1, pp. 486– 506 (2009).* 693 (mar 2009). 486–506. https://doi.org/10.1088/0004-637X/693/1/486
- Ji-hoon Kim, Oscar Agertz, Romain Teyssier, Michael J. Butler, Daniel Ceverino, Jun-Hwan Choi, Robert Feldmann, Ben W. Keller, Alessandro Lupi, Thomas Quinn, Yves Revaz, Spencer Wallace, Nickolay Y. Gnedin, Samuel N. Leitner, Sijing Shen, Britton D. Smith, Robert Thompson, Matthew J. Turk, Tom Abel, Kenza S. Arraki, Samantha M. Benincasa, Sukanya Chakrabarti, Colin DeGraf, Avishai Dekel, Nathan J. Goldbaum, Philip F. Hopkins, Cameron B. Hummels, Anatoly Klypin, Hui Li, Piero Madau, Nir Mandelker, Lucio Mayer, Kentaro Nagamine, Sarah Nickerson, Brian W. O'Shea, Joel R. Primack, Santi Roca-Fàbrega, Vadim Semenov, Ikkoh Shimizu, Christine M. Simpson, Keita Todoroki, James W. Wadsley, John H. Wise, and AGORA Collaboration. 2016. The AGORA High-resolution Galaxy Simulations Comparison Project. II. Isolated Disk Test. *The Astrophysical Journal, Volume 833*, Issue 2, article id. 202, 34 pp. (2016). 833 (dec 2016), 202. https://doi.org/10.3847/1538-4357/83/2/202
- Alan W. McConnachie. 2012. The Observed Properties of Dwarf Galaxies in and around the Local Group. *The Astronomical Journal, Volume 144, Issue 1, article id. 4, 36 pp.* (2012). 144 (jul 2012), 4. https://doi.org/10.1088/0004-6256/144/1/4
- Stacy S. McGaugh. 2005. The Baryonic Tully-Fisher Relation of Galaxies with Extended Rotation Curves and the Stellar Mass of Rotating Galaxies. *The Astrophysical Journal*, *Volume 632, Issue 2, pp. 859-871*. 632 (oct 2005), 859–871. https://doi.org/10.1086/ 432968 arXiv:astro-ph/0506750
- J. F. Navarro, C. S. Frenk, and S. D. M. White. 1996. The Structure of Cold Dark Matter Halos. *The Astrophysical Journal* 462 (may 1996), 563. https://doi.org/10.1086/177173 arXiv:astro-ph/9508025
- Britton D. Smith, Greg L. Bryan, Simon C. O. Glover, Nathan J. Goldbaum, Matthew J. Turk, John Regan, John H. Wise, Hsi-Yu Schive, Tom Abel, Andrew Emerick, Brian W. O'Shea, Peter Anninos, Cameron B. Hummels, and Sadegh Khochfar. 2017. GRACKLE: a chemistry and cooling library for astrophysics. *Monthly Notices* of the Royal Astronomical Society, Volume 466, Issue 2, p.2217-2234 466 (apr 2017),

2217-2234. https://doi.org/10.1093/mnras/stw3291

- James M. Stone and Michael L. Norman. 1992. ZEUS-2D: A radiation magnetohydrodynamics code for astrophysical flows in two space dimensions. I - The hydrodynamic algorithms and tests. Astrophysical Journal Supplement Series (ISSN 0067-0049), vol. 80, no. 2, June 1992, p. 753-790. Research supported by University of Illinois. 80 (jun 1992), 753–790. https://doi.org/10.1086/191680
- Jason Tumlinson, Molly S. Peeples, and Jessica K. Werk. 2017. The Circumgalactic Medium. Annual Review of Astronomy and Astrophysics, vol. 55, issue 1, pp. 389-432 55 (aug 2017), 389-432. https://doi.org/10.1146/annurev-astro-091916-055240
- G. Mark Voit, Greg L. Bryan, Brian W. O'Shea, and Megan Donahue. 2015a. Precipitation-regulated Star Formation in Galaxies. *The Astrophysical Journal Letters, Volume 808, Issue 1, article id. L30, 5 pp. (2015).* 808 (jul 2015), L30. https://doi.org/10.1088/2041-8205/808/1/L30
- G. Mark Voit and Megan Donahue. 2015. Cooling Time, Freefall Time, and Precipitation in the Cores of ACCEPT Galaxy Clusters. *The Astrophysical Journal Letters* 799 (jan 2015), L1. https://doi.org/10.1088/2041-8205/799/1/L1
- G. M. Voit, M. Donahue, G. L. Bryan, and M. McDonald. 2015b. Regulation of star formation in giant galaxies by precipitation, feedback and conduction. *Nature*, *Volume 519, Issue 7542, pp. 203-206 (2015).* 519 (mar 2015), 203–206. https://doi.org/ 10.1038/nature14167
- G. Mark Voit, Megan Donahue, Brian W. O'Shea, Greg L. Bryan, Ming Sun, and Norbert Werner. 2015c. Supernova Sweeping and Black Hole Feedback in Elliptical Galaxies. *The Astrophysical Journal Letters, Volume 803, Issue 2, article id. L21, 5 pp. (2015).* 803 (apr 2015), L21. https://doi.org/10.1088/2041-8205/803/2/L21
- G. Mark Voit, Greg Meece, Yuan Li, Brian W. O'Shea, Greg L. Bryan, and Megan Donahue. 2017. A Global Model for Circumgalactic and Cluster-core Precipitation. *The Astrophysical Journal, Volume 845, Issue 1, article id. 80, 27 pp. (2017).* 845, Article 80 (aug 2017), 80 pages. https://doi.org/10.3847/1538-4357/aa7d04 arXiv:1607.02212
- Jessica K. Werk, J. Xavier Prochaska, Jason Tumlinson, Molly S. Peeples, Todd M. Tripp, Andrew J. Fox, Nicolas Lehner, Christopher Thom, John M. O'Meara, Amanda Brady Ford, Rongmon Bordoloi, Neal Katz, Nicolas Tejos, Benjamin D. Oppenheimer, Romeel Davé, and David H. Weinberg. 2014. The COS-Halos Survey: Physical Conditions and Baryonic Mass in the Low-redshift Circumgalactic Medium. *The Astrophysical Journal*, Volume 792, Issue 1, article id. 8, 21 pp. (2014). 792 (sep 2014), 8. https://doi.org/10.1088/0004-637X/792/1/8