EXPLOSIONS DURING GALAXY FORMATION.
SCALE-FREE SIMULATIONS

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Abstract. When density fluctuations collapse gravitationally out of the expanding cosmological background universe to form galaxies, the secondary energy release which results can affect their subsequent evolution profoundly. We focus here on the effects of one form of such energy release – explosions, such as might result from the supernovae which end the lives of the first generation of massive stars to form inside protogalaxies. We are particularly interested in the consequences of the nonspherical geometry and continuous infall which are characteristic of galaxy formation from realistic initial and boundary conditions. As an idealized model which serves to illustrate and quantify the importance of these effects, we study the effect of explosions on the quasi-spherical objects which form at the intersections of filaments in the plane of a cosmological pancake, as a result of gravitational instability and fragmentation of the pancake. We study the formation and evolution of these “galaxies,” subject to the explosive injection of energy at their centers, by numerical gas dynamical simulation in 3D utilizing our new, anisotropic version of Smoothed Particle Hydrodynamics, Adaptive SPH (“ASPH”), with a P$^3$M gravity solver.

1. INTRODUCTION

Galaxy formation by gravitational condensation out of the expanding cosmological background universe is affected by the complex interplay of gravitational dynamics of collisionless dark matter and the gas dynamics of the baryon-electron fluid, including the feedback on the latter which results when energy is released by the stars and AGN’s that form. Results are presented here of 3D numerical gas dynamical simulations of the effect of this energy release, utilizing our anisotropic Adaptive Smoothed Particle Hydrodynamics (“ASPH”) method. Current computational limitations make it virtually impossible for numerical simulations of the initial value problem involving a realistic initial spectrum of small-amplitude, Gaussian random noise primordial density fluctuations to resolve the full range of length and mass scales necessary to form galaxies and the stars within them at the same time. We choose, instead, to focus here on an idealized model of structure formation which we can hope to resolve more accurately, thereby elucidating some of the most important aspects of the problem which may be relevant, as well, to more realistic initial conditions. We are particularly interested in studying the effects of nonspherical geometry and continuous cosmological infall on the problem of explosion-driven blow-out from galaxies during their formation.

It is well-known that structure formation from Gaussian random noise proceeds in a highly anisotropic way, favoring pancake and filament formation over the formation
of quasi-spherical objects. Our previous work \cite{1,2} has demonstrated, however, that a cosmological pancake, modeled as the nonlinear outcome of a single plane-wave density fluctuation, is subject to a linear gravitational instability which results in the formation of filaments and lumps in the central plane of the pancake. The lumps of collisionless dark matter that form in this way are quasi-spherical and develop a universal density profile which is reminiscent of the universal profiles found from N-body simulations of 3D Gaussian noise density fluctuations in hierarchical clustering models like the CDM model. As such, they provide an ideal test-bed for exploring the gas dynamics of structure formation and feedback effects without the troublesome complexity of Gaussian random noise initial conditions. The pancake problem, moreover, is completely scale-free, once all lengths are expressed in units of the pancake wavelength $\lambda_p$, time is expressed in terms of the cosmic scale factor $a$, divided by the scale factor $a_c$ at which the unperturbed pancake collapses to form density caustics in the dark matter and shocks in the gas, and the energy release is expressed in units of the total energy contained in a comoving cube of side $\lambda_p$. As such, each simulation of galaxy formation via 3D pancake gravitational instability serves to represent the generic behavior independent of the particular mass or collapse epoch of the object which forms. Once the key features of this scale-free problem are delineated, we will later consider the scale-dependent effects of radiative cooling and photoheating. Among the results we seek to quantify in this way are:

- The amount of energy release required to blow the gas out of a dark matter halo.
- The efficiency for ejecting the fraction of gas which is initially responsible for receiving the energy release (and, in the case of supernova explosions, the metallicity associated with the SN ejecta).
- The distinction between “blowout,” in which the energy release results in the escape of some energy and gas into the surrounding IGM but leaves the bulk of the gas in the object unaffected, and “blowaway,” in which most or all of the gas is ejected from the dark matter potential well.
- The energy release rate required to shock-heat the entire IGM by the overlapping effect of energy release from neighboring objects.

2. PANCAKE INSTABILITY AND FRAGMENTATION AS A TEST-BED MODEL FOR GALAXY FORMATION

2.1. Model and Initial Conditions

We consider an Einstein-de Sitter universe (density parameter $\Omega_0 = 1$, cosmological constant $\lambda_0 = 0$) with $\Omega_B = 0.03$ and $\Omega_X = 0.97$ (where $\Omega_B$ and $\Omega_X$ are the contributions of baryons and dark matter to $\Omega_0$, respectively). The initial conditions correspond to the growing mode of a single sinusoidal plane-wave density fluctuation of wavelength $\lambda_p$ and dimensionless wavevector $k = \hat{x}$ (length unit = $\lambda_p$). We adjust the initial amplitude $\delta_i$ such that a density caustic forms in the collisionless dark matter component at scale factor $a = a_c$.

We perturb this system by adding to the initial conditions two transverse, plane-wave density fluctuations with equal wavelength $\lambda_s = \lambda_p$, wavenumbers $k_s$ pointing along the orthogonal vectors $\hat{y}$ and $\hat{z}$, and amplitude $\epsilon_y \delta_i$ and $\epsilon_z \delta_i$, respectively, where $\epsilon_y \ll 1$ and $\epsilon_z \ll 1$. We use the notation $S_{1,\epsilon_y,\epsilon_z}$ to designate a pancake perturbed
by two such transverse perturbation modes. All results presented here refer to the case $S_{1,0,2,0,2}$ unless otherwise noted. The presence of the two perturbation modes will result in the formation of two perpendicular filaments in the plane of the pancake, with a dense, quasi-spherical cluster at the intersection of the filaments.

2.2. Self-Similar Profiles for Dark Matter Halos

In 3D, our previous P^3M simulations of collisionless matter involving $64^3$ particles and $128^3$ grid cells in a comoving cubic box of side equal to $\lambda_p$, with gravitational softening parameter $\eta = 0.3$ grid spacings demonstrated that the quasi-spherical lumps that form as one of the generic outcomes of pancake gravitational instability in 3D, evolve self-similar density profiles of universal shape $\rho \propto r^{-2.75}$. The universal profile is well-approximated as a power-law $\rho \propto r^{-2.75}$ over a large range of density, which flattens somewhat at small radii, a shape which is independent of the details of the initial perturbations to the pancake. This self-similar profile is similar to the universal profile found to fit the results of 3D N-body simulations of the collisionless dark matter in a CDM model [4]. This suggests that this 3D instability of cosmological pancakes which leads generically to the formation of such quasi-spherical dark matter halos may be used as an alternative to the details of the CDM model with its Gaussian random noise initial density fluctuations as a test-bed in which to study halo and galaxy formation further.

To illustrate the universal density profile associated with this pancake instability, we show in Figure 1 results from [2] and [3] for one particular case, $S_{1,0,2,0,2}$, for various values of the expansion factor, as well as a summary of results for several different perturbation modes, at $a/a_c = 7$.

3. THE EFFECT OF EXPLOSIVE ENERGY RELEASE ON GALAXY FORMATION: BLOW-AWAY AMIDST CONTINUOUS INFALL

Galaxy formation which leads to star formation can be affected by feedback when stars evolve to the point of supernova (SN) explosions and the resulting shock-heating and outward acceleration of interstellar and intergalactic gas. Previous attempts to model this effect have typically been along one of three lines, that which adopts a smooth initial gas distribution in a galaxy-like, fixed dark matter gravitational potential well (e.g. [5]), that which considers a single, isolated, but evolving, density fluctuation (i.e. without merging, infall or the effects of external tidal forces) (e.g. [6]), and that in which the galaxy forms by condensation out of Gaussian random noise primordial density fluctuations such as in the CDM model (e.g. [7], [8], [9], [10], [11], [12]). In the first case, the computational ability to resolve shocks which propagate away from the sites of explosive energy release is generally greater, while the last is perhaps more realistic in terms of the initial and boundary conditions, but the resolving of shocks is still generally quite poor.

We compromise here between these two limits by using the pancake instability problem as the model of galaxy formation in which to explore the feedback effect of the explosive release of energy by SNe inside a protogalaxy. This affords some of the benefit of greater ease of the first approach mentioned above in resolving the explosion-driven shocks which are the crucial element in blowing gas out and away. It also provides a self-consistent cosmological origin and boundary condition for a protogalaxy or cluster, including the important effect of anisotropic gravitational...
Figure 1. Top Panel: Density profiles (spherically averaged, in units of $\langle \rho \rangle$, the average background density) versus radius from halo center (in units of $\lambda_p$) for mode $S_{1,0.2,0.2}$ at $a/a_c = 1$ (dot-short dash), 2 (long dash), 3 (short dash), 4.5 (dotted), and 7 (solid); Bottom Panel: Density profiles at $a/a_c = 7$ for several different modes of pancake perturbation: $S_{1,1,1}$ (solid), $S_{1,0.5,0.5}$ (dotted), $S_{1,0.4,0.4}$ (short dash), $S_{1,0.3,0.3}$ (long dash), $S_{1,0.2,0.2}$ (dot-short dash), $S_{1,0.1,0.1}$ (dot-long dash), $S_{1,0.5,0.25}$ (short dash-long dash)([2],[3])
collapsible and continuous infall.

Sharing the initial conditions described above for the formation of a dark matter halo via 3D pancake instability mode $S_{1,0.2,0.2}$ is an additional component of baryon-electron gas. We model the explosive release of energy due to SNe in terms of a single impulsive explosion which may represent a starburst or the collective effect of multiple SNe. We initiate the explosion by waiting until the first gas particles at the center of our dark matter halo reach a density contrast relative to the average background density, $\rho/\langle \rho \rangle$, exceeding $10^3$, at which point we suddenly multiply the thermal energy of these particles by a factor $\chi$ and share some of the explosion energy smoothly amongst their nearest neighbor particles via ASPH kernel smoothing as well. This occurs at $a/a_c = 2.06$. While we have performed a series of simulations for different values of $\chi$, we shall report here only the results for two limiting cases: $\chi = 0$ (no explosion) and $\chi = 10^3$ (blowaway regime). Simulations end at an expansion factor $a/a_c = 3$. (Note: The proper, numerical prescription for depositing the energy of explosions in the interstellar gas surrounding the explosion site is a complicated question, dependent as it is on explosion details which are unresolvable by current numerical treatments. Some recent discussion of this question is contained in [13] and [14], including the question of the fraction of the energy of a given SN explosion which ends up as kinetic energy of the SN remnant rather than as thermal energy. However, since the simulations described here are adiabatic and neglect radiative cooling, it is self-consistent for us to deposit the entire explosion energy initially as thermal energy.)

All our gas dynamical simulations are based upon the new 3D version of our ASPH method ([13],[14],[15]), coupled to a P$^3$M gravity solver. The simulations reported here use $32^3$ gas particles, $32^3$ dark matter particles (with unequal particle masses, $m_{\text{dark}}/m_{\text{gas}} = \Omega_X/\Omega_B = 32.3$), and a P$^3$M grid of $64^3$ cells with softening length $\eta = 0.3$ grid spacings.

4. RESULTS

In the absence of explosion, the simulation produces two orthogonal filaments within the pancake central plane at whose intersection is located a denser, quasi-spherical ball of gas which sits in the gravitational potential well of a dense, quasi-spherical dark matter halo like that in Figure 1. In the case with explosion, we found that away from the central object, the pancake and the filaments within it are hardly affected. However, gas has been blown out of the center and some exterior gas which was infalling along directions perpendicular to the pancake plane has been swept back out, as well, some as far as to the outer edge of the box.

In Figure 2, we show a shaded contour plot of the gas temperature at $a/a_c = 3$, in a plane perpendicular to the pancake and intersecting the center of the central cluster. The explosion is confined by the gas in the plane of the pancake (seen edge-on on this figure) outside the central object, with the hottest gas at the very center. The filaments are hardly affected, however, nor is the shocked pancake gas far from the central object. This edge-on view of the pancake reveals that a major blow-out has occurred in which the explosion, led by an outer shock, has propagated all the way to the edge of the box, half-way to the nearest neighbor pancake, and collided there with the explosion shock expanding away from the neighboring pancakes’ central object and toward the pancake in this box. The temperature plot reveals multiple shocks interior to the explosion, especially along the symmetry axis of the blow-out. Although the central object in which the explosion took place was quasi-spherical, the existence of
the pancake plane and of the filaments which intersect at the location of the central dark halo ensure that a highly anisotropic explosion results and serves to channel the energy and mass ejection outward along the symmetry axis.

Image Plane = Central Cross Section. \( a/a_c = 3.00 \)

![Image Plane = Central Cross Section. \( a/a_c = 3.00 \)](image)

**Figure 2.** Dimensionless Gas Temperature [i.e. internal energy per gram in units of \( (2401/4)\alpha_0^2(a/a_c)^{-4} \)] in the plane perpendicular to the pancake, a cross section view which intersects the center of the central cluster.

Velocity arrows for the gas particles at \( a/a_c = 3 \) are displayed in Figures 3 and 4. Figure 3 shows a thin slice of the computational volume which contains the pancake central plane (i.e. a top view looking down on the pancake central plane). Figure 4 shows a slice perpendicular to the pancake (that is, the same plane as in Figure 2). These show that outflow is restricted to the symmetry axis, while infall continues within the pancake plane and especially inward along the filaments.

The effect of the explosion in blowing gas away is illustrated by Figure 5, in which different particle groups are distinguished according to their fate with and without the explosion. In the top panel, the solid dots show the particles which were the original recipients of the explosion energy and, by implication, the metal-enriched SN ejecta, which were previously located at the very center of the central dark halo at \( a/a_c = 2.06 \). Gas initially outside this core region which was within the halo defined
Figure 3. Velocity Field at $a/a_c = 3$ in the pancake central plane, for the case with explosion. Each arrow corresponds to a simulation gas particle in a thin slice containing the pancake symmetry plane. Top panel: Full image; Bottom panel: zoom of the central region.
Figure 4. Velocity Field at $a/a_c = 3$ in the plane perpendicular to the pancake, for the case with explosion. Each arrow corresponds to a simulation gas particle in a thin slice centered on the image plane shown in Figure 2. Top panel: Full image; Bottom panel: zoom of the central region.
according to a mean overdensity $\rho/\langle \rho \rangle \geq 200$ but which did not receive the initial explosion energy or ejecta directly is shown as open dots. All of the gas originally inside the halo when the explosion occurred has been blown away by $a/a_c = 3.0$. The lower panel of Figure 5 shows all those gas particles which were found to be inside the central halo with mean overdensity $\rho/\langle \rho \rangle \geq 200$ at $a/a_c = 3$ in the case with no explosion but which are not inside this overdensity at $a/a_c = 3.0$ in the case with the explosion.

The effect of the explosion on the build-up of the gas mass of the “galaxy” by continuous infall is illustrated by the plot in Figure 6 of the collapsed gas fraction in the box, defined as the gas of overdensity $\rho/\langle \rho \rangle \geq 200$, for the cases with and without the explosion. With no explosion, the central mass grows continuously from $a/a_c = 2$ to $a/a_c = 3$ to encompass 10% of all the mass in the box. With the explosion, however, all the gas in the central halo is blown away shortly after the explosion occurs at $a/a_c = 2.06$, but by $a/a_c = 2.7$, unobstructed infall within the pancake plane and along the filaments starts to resupply the central halo with gas at a significant rate.

5. SUMMARY

• We find that blow-out and blow-away are generically anisotropic events which channel energy and mass loss outward preferentially along the symmetry axis of the local pancake and away from the intersections of filaments in the pancake plane.
• This means that metal ejection from dwarf galaxies at high redshift due to explosive energy release is less likely to pollute the local filaments and pancake in which the dwarf galaxies reside and more likely to channel the metals away from those denser regions.
• Despite the complete blow-away of gas initially in the dark matter potential well of the “galaxy” by the large explosion simulated here, continuous infall is not completely halted in the directions away from the preferred direction of blow-out, so infall partially replenishes the gas which is blown-away.

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Figure 5. Gas particle positions projected onto the image plane of Figure 2. Case with explosion, at $a/a_c = 3$. Top panel: particles that were located in the central cluster when the explosion occurred. The filled symbols indicate the particles that were metal-enriched by the explosion itself. The line and circle indicate respectively the location of the pancake plane and the location of the cluster in the absence of explosion. The radius of the circle is that which enclosed matter with average density $\rho/\langle \rho \rangle \geq 200$ inside cluster in absence of the explosion. Bottom panel: particle with density smaller than $200\langle \rho \rangle$ whose density would be larger than $200\langle \rho \rangle$ in the absence of explosion.
Figure 6. Fraction of gas with overdensity $\rho/\langle \rho \rangle \geq 200$ versus $a/a_c$

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