ENTROPY EVOLUTION IN GALAXY GROUPS AND CLUSTERS: A COMPARISON OF EXTERNAL AND INTERNAL HEATING

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ABSTRACT

The entropy in hot, X-ray-emitting gas in galaxy groups and clusters is a measure of past heating events, except for the entropy lost by radiation from denser regions. Observations of galaxy groups indicate higher entropies than can be achieved in the accretion shock experienced by gas when it fell into the dark halos. These observations generally refer to the dense, most luminous inner regions where the gas that first entered the halo may still reside. It has been proposed that this nongravitational entropy excess results from some heating process in the early universe that is external to the group and cluster halos and that it occurred before most of the gas had entered the dark halos. This universal heating of cosmic gas could be due to active galactic nuclei (AGNs), Population III stars, or some as yet unidentified source. Alternatively, the heating of the hot gas in groups may be produced internally by Type II supernovae when the galactic stars in these systems formed. We investigate here the consequences of various amounts of external, high-redshift heating with a suite of gasdynamical calculations. We consider the influence of radiation losses and distributed mass dropout on the X-ray luminosity and emission-weighted temperature of the hot gas as well as its central entropy. In general, we find that externally heated flows are unsatisfactory; when the heating is high enough to bring the X-ray luminosities into agreement with observations, the gas entropy is too high. We compare these solutions with flows that are internally heated by Type II supernovae; this type of heating depends on the initial mass function (IMF) and the efficiency that the supernova energy is conveyed to the hot gas. These internally heated flows give much better agreement with X-ray observations of galaxy groups and are insensitive to the levels of supernova heating that we consider as well as to the epoch and spatial distribution of the supernova heating process. However, to fit X-ray observations, a large fraction of the energy produced by high-redshift Type II supernovae must heat the hot gas if the number of supernovae is based on a Salpeter IMF. Alternatively, only about 20\% of the Type II supernova energy would be required to heat the gas if the IMF has a flatter slope than Salpeter, as suggested by stellar mass--to--light ratios.

Subject headings: cooling flows — galaxies: elliptical and lenticular, cD — galaxies: evolution — intergalactic medium — X-rays: galaxies — X-rays: galaxies: clusters

1. INTRODUCTION

In a perfect, starless ΛCDM hierarchical universe filled with adiabatic gas and NFW (Navarro, Frenk, & White 1996) dark halos, the bolometric X-ray bremsstrahlung luminosities of galaxy groups and clusters would scale in a self-similar fashion with gas temperature, \( L \propto T^2 \) (Kaiser 1986; Evrard & Henry 1991). However, in our particular universe this relation is somewhat steeper (\( L \propto T^3 \); e.g., Arnaud & Evrard 1999) and becomes very steep (at least \( L \propto T^4 \)) for groups having \( T \lesssim 1 \) keV (Helsdon & Ponman 2000a). The observed properties of galaxy groups differ from those of massive clusters in several other respects. Groups have a lower baryon fraction \( f_B = \Omega_\text{b}/\Omega_0 \) (David 1997; Renzini 1997), and a larger fraction of group baryons are stellar (e.g., David et al. 1990; David & Blumenthal 1992). Finally, the entropy factor \( S \equiv T/n_\text{e}^{2/3} \) evaluated at 0.1\( r_{\text{vir}} \) for groups exceeds the self-similar expectation, indicating that groups have received an additional entropy \( S \sim 100 \text{ keV cm}^2 \). If a comparable entropy increment were present in the hot gas in massive clusters, it would be difficult to detect because of the much larger entropy that the gas acquires passing through stronger accretion shocks that surround more massive clusters. The minimum entropy observed in groups is has been referred to as the “entropy floor” (Ponman, Cannon, & Navarro 1999; Lloyd-Davies, Ponman, & Cannon 2000).

These deviations from self-similarity have led to the hypothesis that gas in groups experienced some additional early heating before (or when) it flowed into the group halos. Early “preheating” by 0.5–1.5 keV per particle could explain the aberrant behavior of groups in both the \( L-T \) and \( S-T \) plots. Furthermore, since this level of heating would only be noticed in the shallower potentials of galaxy groups, most authors have adopted a much stronger assumption, that all baryonic gas, including gas currently in both groups and clusters, experienced some “nongravitational” heating (star formation, Population III stars, active galactic nuclei [AGNs], etc.) prior to its entry into the dark halos.

As a result of its dissipative nature, the gas entropy observed in galaxy groups today does not in itself indicate a unique heating history. Entropy increases in shocks and is lost with radiative cooling. Nevertheless, the level of heating required to heat all the gas at the same (high) redshift in “preheating” scenarios generally exceeds that produced by Type II supernovae (SNe II) following normal star formation: \( \sim 0.2 \text{ keV per particle} \). In this estimate we assume that
10% of the baryons form into stars (Fukugita, Hogan, & Peebles 1998) with a typical Salpeter IMF, producing SNe II that heat the remaining gas with 100% efficiency.

Nevertheless, many theoretical papers have appeared recently with estimates of the assumed universal preheating necessary to produce the “entropy floor” in groups and the related departure from $L$-$T$ self-similarity (e.g., Knight & Ponman 1997; Cavaliere, Menci, & Tozzi 1997; Balogh, Babul, & Patton 1999; Cavaliere, Giacconi, & Menci 2000; Loewenstein 2000; Tozzi & Norman 2001; Valangeas & Silk 1999; Kravtsov & Yepes 2000). For a given energy release, the final entropy is larger if the energy is applied when the gas density is low. Therefore, most of these authors have assumed that the gas was heated (by some unspecified agency) while in a low-density intergalactic environment (at redshift $z \leq 7$) before it flowed into the galaxy group potentials.

Independent support for strong universal heating has come from estimates of the collective emission from gas-filled group halos at large redshifts that appear to exceed the observed soft X-ray background radiation (Pen 1999; Wu, Fabian, & Nulsen 2001, hereafter WFN01). These authors suggest that the intergalactic gas was heated to $T \gtrsim T_{\text{vir}}$ so that little of it flowed into group halos at early times. However, SN II–driven galactic winds are expected to develop immediately in these small halos, perhaps reducing the contribution of groups to the unresolved X-ray background. In addition, warm to hot diffuse intergalactic gas at temperatures $10^5 \lesssim T \lesssim 10^7$ K can result from (gravitationally produced) shocks in large-scale filaments (Cen & Ostriker 1999; Davé et al. 2001). Moreover, in the cosmological simulations of Davé et al. (2001) most of the warm to hot gas that contributes to the unresolved soft X-ray background is at low densities and diffusely distributed, not concentrated in (group) halos as assumed by Pen (1999) and WFN01. Consequently, Davé et al. (2001) predict a soft X-ray flux \( \sim 100 \) times less than that of Pen (1999) and WFN01, sufficiently low to be consistent with the observed (unresolved) background. Although the non-gravitational heating of intergalactic gas postulated by Pen (1999) and WFN01 may occur, it is not supported by more detailed cosmological simulations.

Tozzi & Norman (2001) study the consequences of universal intergalactic heating prior to collapse into dark halos in a flat ΛCDM cosmology. In their approximate hydrodynamic models with radiative cooling, all cooled baryonic gas is assumed to collect at the very center. The universal energy input (at $z > 1$) they require to match the observed “entropy floor” is in excess of normal SN II expectations. In their preferred models, Tozzi & Norman (2001) assume that the intergalactic gas (heated to $\sim T_{\text{vir}}$ for groups) enters the group halos adiabatically, i.e., without shocking. As a consequence, the radial entropy profile for the Tozzi-Norman (2001) externally preheated galaxy groups is almost constant out to the virial radius $r_{\text{vir}}$, unlike those observed by Lloyd-Davies et al. (1999) for which $S \propto r$, and the gas temperature gradients of these Tozzi-Norman (2001) models are quite negative throughout, e.g., $d \log T / d \log r \approx -0.4$ at $r \approx 0.1 r_{\text{vir}}$, unlike the nearly constant temperature profiles observed. Both of these key results of adiabatic inflow are in conflict with observed groups, at least within the small region that can be observed, $r \lesssim (0.1-0.4)r_{\text{vir}}$. By contrast, an internal heating scenario is proposed by Loewenstein (2000), who estimates the amount of heating required after the hot gas has reached hydrostatic equilibrium in group and cluster dark halos. From a series of approximate static hot gas models, Loewenstein (2000) argues that most of the heating occurred during or after the assembly of the group or cluster gas, not throughout the intergalactic gas at an earlier time. We are in agreement with his interpretation, although it may be a minority opinion at the present time.

Perhaps the most convincing evidence that the origin and evolution of hot gas in galaxy groups can be understood with normal star formation and other standard astrophysical assumptions is the success of our own detailed calculations for the giant elliptical NGC 4472 (Brighenti & Mathews 1999a), the dominant galaxy in a small Virgo subcluster. This is a complete gasdynamical calculation beginning with a top-hat perturbation in a flat cosmology. The gas evolves in a growing NFW dark halo, produces stars and SN II heating, and forms a central galaxy, and the stars lose mass and produce Type Ia supernovae (SNe Ia). After 13 Gyr we were able to match the radial variation of density, temperature, and iron abundance observed in NGC 4472 (Brighenti & Mathews 1999b). The agreement is excellent everywhere except within $\sim 1$ kpc from the center where the gas density is too high; we now think this is due to additional support by magnetic stresses there. Our models also agree with the present-day entropy variation and luminosity in NGC 4472. In particular, our models for NGC 4472 produce the “entropy floor” in the S-$T$ plot and the observed deviation from the L-$T$ self-similar relation without universal preheating. In addition, they go much further in fitting the radial profiles of density, temperature, and iron abundance (Buote 2000a) observed in NGC 4472.

The preheating controversy devolves on a choice between internal supernova heating during galaxy group formation and external (universal) heating by AGNs or some other agency at an early time. Given the apparent success of our calculations for NGC 4472, it seems possible that the “entropy floor” and L-$T$ similarity breaking in groups can be explained with normal star formation. However, the widely discussed preheating hypothesis can under some conditions also provide the necessary similarity breaking. Our objective in this paper is to perform a series of gasdynamical calculations that explore the consequences of various levels of external preheating that span the full range from galaxy groups to rich clusters. Several sets of progressively more sophisticated calculations are considered, beginning with purely adiabatic flow. These externally heated cooling flows are compared with flows that only experience internal supernova-based heating. We shall find that the latter mode of heating is generally quite satisfactory in fitting the X-ray data, but the initial mass function (IMF) may need to be flatter than Salpeter.

2. OVERVIEW OF GASDYNAMICS OF GALAXY CLUSTERS AND GROUPS

In order to compare our gasdynamical calculations with internal supernova heating with discussions of external preheating in the current literature, we consider gas flowing into dark halos of three masses representing galaxy groups, poor clusters, and rich clusters. The dark halo evolution is similar in all models. These structures all begin with a top-hat perturbation in a ΛCDM universe [$\Omega_0 = 0.3$, $\Lambda = 0.7$, $h = H_0/(100 \text{ km} \text{ s}^{-1} \text{ Mpc}) = 0.725$], which converts to a dark matter NFW profile at very high redshifts.
The dark halos are assumed to grow masswise from the inside out as described by Bertchinger (1985). The dark matter flow pattern consists of an outer, converging smooth collisionless flow that attaches to a stationary NFW core having a concentration appropriate to its current virial mass. The time-dependent intersection radius of the stationary halo with the converging flow is chosen to conserve dark matter mass.

Baryonic gas with mean density $\Omega_b = 0.039(h/0.7)^{-2}$ (Burles & Tytler 1998a, 1998b) flows into the evolving dark matter potential. However, in order to explore the cosmic preheating hypothesis using the same approach as often employed in the current literature, we may choose to “reset” the density and temperature (and therefore the entropy) of the baryonic gas to be spatially uniform at a very early time $t_0 = 0.5$ Gyr (redshift $z_h = 9$) when the stationary dark halo mass is only 0.1–0.2 of its current virial mass. At the reset the gas velocity is assumed to retain its velocity in the cosmic flow outside the NFW halo at time $t_0$, but within the halo the gas velocity is set to zero. This artificial reset of the gas parameters at this high redshift often has no long-lasting influence on the gasdynamics; however, if the gas temperature is less than the virial temperature of the dark matter structures at time $t_0$, shocks may develop resulting in entropy fluctuations that persist until the present time $t_\text{ref} = 13$ Gyr.

In the following discussion we consider a suite of increasingly more realistic physical models for the baryonic component. For dark halos of each mass, the baryonic gas is assumed to be preheated at time $t_0 = 0.5$ Gyr by varying amounts. For the first set of models, we assume that the gas flow is perfectly adiabatic but with adiabatic (nonradiating) shocks, so most of the entropy increase occurs in the accretion shock transition. In the next series of models we include radiative cooling and allow the cooled gas to accumulate at the origin as in the models of Tozzi & Norman (2001). Next we repeat some of these models with a cooling recipe similar to that used by Nulsen & Fabian (1997) in which the cooled gas accumulates not at the origin but in spatially extended structures, as if it had formed into a collisionless stellar system. This type of flow is similar to the mass dropout flows discussed by Knight & Ponman (1997) (but who assumed Bertchinger 1985 dark halos in a $\Omega_0 = 1$ cosmology with a large baryon fraction and no heating). For each series of calculations we consider a range of virial masses and assumed entropies corresponding to different levels of external preheating at the reset time. Finally, we repeat the same calculations again allowing for star formation with various amounts of energy released in SN II feedback. In this series of models, which resembles our earlier calculation for NGC 4472, the SN II heating at early times is internal, a natural consequence of star formation. These models also include stellar mass loss and heating by SNe Ia.

2.1. Observational Data

The X-ray luminosity varies over a factor $\gtrsim 10^4$ from galaxy groups to the richest clusters, and the gas temperature spans a range of $\sim 30$. Because of the inhomogeneous observational data available over this vast range of parameters and the various bandpasses that have been used in these observations, we shall consider only those observations for which the bolometric X-ray luminosities are determined. All data are corrected to our assumed $H_0 = 100 h = 72.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

For galaxy group luminosities and temperatures we choose the recent observations of Helsdon & Ponman (2000a) for loose groups. More recently, these authors have shown that there is no distinction in the X-ray properties of loose and compact groups (Helsdon & Ponman 2000b). Helsdon & Ponman (2000b) list ROSAT PSPC bolometric luminosities for 24 groups. Unfortunately, these groups are observed out to a radius that is typically only $\sim 0.1–0.2$ of the virial radius, so Helsdon & Ponman (2000b) provide for each group an approximate correction factor to estimate the total bolometric luminosity within the virial radius; we have employed this correction in their group data plotted with open squares in Figure 1. The $L-T$ variation is quite steep (and uncertain) for these groups, $L \propto T^{-4.9\pm0.8}$.

For the entropy in galaxy groups and clusters we use the data of Lloyd-Davies et al. (2000), who estimate the entropy factor $S = T h^{-2/3}$ at 0.1$r_{\text{vir}}$.

For a sample of poor and rich clusters we use data for 24 clusters collected by Arnaud & Evrard (1999) from many disparate authors using different X-ray satellites. In selecting this sample Arnaud & Evrard (1999) avoided clusters with strong cooling flows. The Arnaud-Evrard (1999) bolometric luminosities have not been corrected to the virial radius, but this correction may not be large. For example, the mean correction found by Helsdon & Ponman (2000b) for the groups is only a factor of $\sim 1.5 \sim 10^{0.2}$. The Arnaud-Evrard (1999) data, shown with crosses in Figure 1, can be fitted with $L \propto T^{2.88\pm0.15}$, which is also steeper than adiabatic similarity $L \propto T^2$.

Allen & Fabian (1998) emphasize the important effect that a strong cooling flow has on the $L-T$ relation. About 70%–90% of rich clusters have cooling flow cores. Since the gas temperature has a steeper radial gradient (and is generally lower) in clusters with strong cooling cores, it is unclear which temperature is appropriate to enter in the $L-T$ diagram. If the ASCA X-ray spectra of Allen & Fabian (1998) are fitted with isothermal models (their model A), the cooling flow clusters lie at lower temperatures (and higher luminosities) than non–cooling flow clusters as shown in Figure 1. The non–cooling flow clusters have slope $L \propto T^{2.90\pm0.29}$, very similar to the Arnaud-Evrard (1999) slope, and in fact appear to be fully consistent with the overlapping Arnaud-Evrard (1999) data. Alternatively, if the X-ray spectra of cooling flow clusters are fitted with a combination of single-temperature thermal emission and XSPEC cooling flow models (in which the emitted spectrum is an integrated sum over many gas temperatures) as in model C of Allen & Fabian (1998), then the background (uncooled) gas temperatures of cooling flow clusters increase and become very similar to those of the non–cooling flow clusters in the Allen-Fabian (1998) sample. This is a clear example of the substantial scatter that can occur in the $L-T$ diagram arising from the data reduction procedure when a wide range of temperatures contribute to the observed spectrum. In a related approach, Markovitch (1998) showed that the $L-T$ correlation tightened considerably when the cooling flow cores are removed from both the luminosity and temperature data.

When data for all groups and clusters are compared in Figure 1, it can be seen that the Arnaud-Evrard (1999) data have the same slope and ordinate as the non–cooling flow Allen-Fabian (1998) clusters. This is expected since the Arnaud-Evrard (1999) clusters were also chosen to have weak cooling flow cores. If Arnaud & Evrard (1999) had
Fig. 1.—Variation of X-ray bolometric luminosity with emission-weighted temperature. Open squares: groups from Helsdon & Ponman (2000a); crosses: clusters from Arnaud & Evrard (1999); open circles: clusters from Allen & Fabian (1998); open triangles: non–cooling flow clusters from Allen & Fabian (1998). The dashed line shows the (unnormalized) $L \propto T^2$ relation expected if the hot gas were adiabatic and emitted bremsstrahlung radiation. Panels (a)-(d) show results of calculations for adiabatic (AD), radiative cooling (CO), mass dropout (DO), and galaxy formation (GA) models. The filled circles, squares, and triangles are results of gasdynamical calculations at time 13 Gyr for groups, poor clusters, and clusters, respectively. Note that the computed luminosities and temperatures for the two DO models for groups DOg1 and DOg2 are almost identical.

Fig. 2.—Plot of the entropy factor $S = 10^n_{\gamma} T_{\text{e}}^{-2/3}$ evaluated at radius $0.1 r_{\mathrm{vir}}$ against emission-weighted temperature. Each panel shows the entropy data (filled squares) from Lloyd-Davies et al. (2000) with a dashed line $S \propto T$ passing through the rich clusters. Open circles in each of panels (a)-(d) show results of calculations for adiabatic (AD), radiative cooling (CO), mass dropout (DO), and galaxy formation (GA) models. The radius of the open circle increases with the amount of heating as characterized by the nomenclature 1–4 as described in the text.

Instead chosen clusters at random, they would have found a much larger number of normal cooling flow clusters scattered above their correlation in Figure 1, similar to the cooling flow clusters in the Allen & Fabian (1998) sample.
The identification of the Arnaud-Evrard (1999) clusters with the lower envelope of the correlation in the L-T plot also explains why the Helsdon-Ponman (2000b) poor groups with the greatest temperatures may seem slightly over luminous relative to adjacent members of the Arnaud-Evrard (1999) sample having the lowest temperatures. This lack of consistency and apparent continuity between the various data sets demonstrates how systematic shifts in the L-T plot may arise from different methods of sample selection and data reduction for the majority of cooling flows in which the intrinsic temperature necessarily varies over a wide range.

Since the L-T data for groups are so important in setting limits on the amount of cosmic preheating, some possible systematic trends should be recognized. Just as with rich clusters, groups with strong cooling flows tend to occupy the upper envelope of the group data in Figure 1. To demonstrate this, we use the sample of 12 galaxy groups studied by Buote (2000b), in which the data were reduced with an XSPEC cooling flow model with a determination of the cooling rate \( \dot{M} \). If the Buote (2000b) data are bisected with an XSPEC cooling flow model with a determination of the cooling rate \( \dot{M} \), then the data set demonstrates this, we use the sample of 12 galaxy groups studied by Buote (2000b), in which the data were reduced with an XSPEC cooling flow model with a determination of the cooling rate \( \dot{M} \). If the Buote (2000b) data are bisected with a line of slope \( L \propto T^3 \) or \( T^4 \), the mean cooling flow rate of groups that lie above the line, \( \langle \dot{M} \rangle = 21 M_\odot \text{ yr}^{-1} \), is much greater than the mean of the six groups below, \( \langle \dot{M} \rangle = 6.2 M_\odot \text{ yr}^{-1} \). X-ray emission from the more luminous half-sample has spuriously lower temperatures as a result of strong cooling flows associated with the central galaxy. This is an important distinction for our models since we are interested in groups in which a strong cooling flow develops around a dominant, luminous elliptical galaxy located at the group center. For this reason we expect our successful models with concentrated cooling flows to lie near the upper envelope of the Helsdon-Ponman (2000b) group data. Additional scatter in the L-T data for groups is introduced by the variable physical extents of the X-ray observations relative to the virial radius for each group.

Finally, the choice of cosmology has some influence on the observational data. In extrapolating \( L \) to the virial radius, Helsdon & Ponman (2000a) used the standard cold dark matter (SCDM) adiabatic results of Navarro, Frenk, & White (1995) to derive \( r_{vir} \) from the observed gas temperature. Our adiabatic models and LCDM variables give \( r_{vir} \approx 2.3(T/5.1 \text{ keV})^{1/2} \text{ Mpc} \), which is only about 10% smaller than that used by Helsdon & Ponman (2000a), probably within the observational and computational uncertainties.

2.2. Growth of NFW Profiles

We consider three virial masses, \( M_{\text{vir}} = 4.7 \times 10^{13}, 2.2 \times 10^{14}, \) and \( 1.2 \times 10^{15} M_\odot \), which span a range from galaxy groups to moderately rich clusters. These dark halos form as a result of a top-hat perturbation in a flat ΛCDM cosmology, \( \Omega_0 = 0.3, \Lambda = 0.7, \) and \( h_0 = 72.5 \text{ km s}^{-1} \text{ Mpc}^{-1} \), chosen so that the current time is exactly \( t_0 = 13 \text{ Gyr} \). The baryonic component \( \Omega_b = 0.039(h/0.7)^2 \) is such that \( \Omega_b/\Omega_0 = 0.123 \). When a top-hat perturbation is imposed, the dark matter flows toward the perturbation as a pressure-free gas and accumulates in an extended, static, spherically symmetric structure. This structure is assumed to have the standard NFW halo profile for which the virial mass is \( M_{\text{vir}} = (4\pi/3)\rho_{\text{crit}} \Delta \rho_{\text{c}} \). Here \( \Delta = 178 (\Omega_m^{0.45} \approx 100 \) (Eke, Navarro, & Frenk 1998) and \( \rho_{\text{c}} = 3H_0^2/8\pi G = 1.07 \times 10^{-29} \text{ g cm}^{-3} \) is the critical density. The shape of the dark halo at any time is \( M(r) = M_{\text{vir}} f(y)/f(c) \), where \( f(y) = \ln(1 + y) - y/(1 + y), \ y = r/r_{\text{vir}}, \) and \( c = r_{\text{vir}}/r_s \) is the concentration. Cosmological simulations show that the concentration decreases slowly with \( M_{\text{vir}} \) and redshift (Bullock et al. 2001). We ignore the redshift variation, i.e., \( c = 8.35(M_{\text{vir}} h^{-1}/10^{14} M_\odot)^{-0.091} \). The virial radii for the three dark halos are \( r_{\text{vir}} = 895, 1500, \) and \( 2640 \text{ kpc} \), or \( \log r_{\text{vir}} = 2.95, 3.17, \) and 3.42, respectively.

The complete solution for the dynamical growth of a locally overdense region of collisionless dark matter in a flat Einstein–de Sitter universe was solved by Bertschinger (1985). He showed that the converging pressure-free flow accumulates in an essentially stationary core that grows masswise from the inside outward, as if newly arriving matter were added at the outer boundary of the core. Since Bertschinger (1985) made no allowance for the hierarchical, three-dimensional nature of mass accumulation, the mass profile in his stationary core differs from the more appropriate NFW shape. We adapt the basic physics of Bertschinger’s (1985) collisionless solution for the evolution of a dark matter overdensity to our flat ΛCDM cosmology by computing the pressure-free collapse of the dark matter until it accumulates at the outer boundary of a stationary halo that is required to have the more correct NFW profile (Brighenti & Mathews 1999b). The halo grows with time (from the inside out) at a cosmologically appropriate rate, conserving dark mass. However, at very high redshifts \( z > z_\gamma = 15 \) this simple recipe breaks down for large \( M_{\text{vir}} \) because the internal mass distribution of the NFW halo can be less than that of the converging ΛCDM flow at every radius. When this mismatch occurs at high redshift, we assume that the dark matter collapses into an extended, mass-conserving power-law halo \( M(r) \propto r^\rho \) within 40 kpc, which resembles the inner profile of an NFW halo. This transition in the dark matter halo is particularly necessary for the most massive halo we consider; NFW halos of smaller mass intersect the ΛCDM flow at very high redshifts \( z_{\text{vir}} = 15 \). We find that the exact shape of the temporary, non-NFW dark halo for \( z > z_\gamma \) has only a small influence on the integrated properties of the gas at time \( t_\gamma = 13 \text{ Gyr} \). While none of our conclusions are affected by assumed dark halo structure at \( z > z_\gamma \), it is good to keep in mind that some of our computed results (final \( L, T, \) etc.) are uncertain at the \( \sim 20\% \) level. Finally, we note that the baryonic gas does not exactly follow the dark matter in the external ΛCDM flow since in general the gas velocity is slowed by radial pressure gradients.

2.3. Gasdynamics

The equations for one-dimensional Eulerian gasdynamics that we use here are described in detail in Brighenti & Mathews (1999a). They are solved with an extensively modified one-dimensional spherical version of the Eulerian code ZEUS (Stone & Norman 1992). The pressure-free dark matter and the baryonic gas are computed as two separate fluids that interact gravitationally. The size of spatial zones increases logarithmically. We use “outflow” boundary conditions at the outermost spherical zone where the Hubble flow recedes supersonically out of the grid and the flow velocity vanishes at the origin. Sink terms for radiative cooling and distributed mass dropout are included in the appropriate models. For those models involving gas flow within optical galaxies, the gasdynamic equations have additional source terms for stellar mass loss and heating by stars and SNe Ia. The full set of equations is described in Brighenti & Mathews (1999a).
2.4. External Preheating

The characteristic virial temperature of an NFW halo can be found directly from the condition for hydrostatic equilibrium, \( T \sim (\rho_m/k)GM_{\text{vir}}/r_{\text{vir}} \propto r_{\text{vir}}^{-3/2} \), since by definition the mean density within the virial radius is always \( \Delta \rho_m \). The X-ray luminosity for pure bremsstrahlung emission, with emission coefficient \( \propto T^{-1/2} \), is \( L \propto \rho^2 A r_{\text{vir}}^3 \propto \rho^3 T^{-1/2} \), where the characteristic gas density \( \rho \) is assumed to scale with the dark halo density (e.g., Kaiser 1986, 1991). Therefore, we expect \( L \propto T^3 \) provided that the following assumptions hold: (1) the gas is in hydrostatic equilibrium bound to homologously identical halos, (2) the gas density profiles are homologous in the variable \( r/r_{\text{vir}} \) for all clusters, (3) the ratio of gas to dark mass is identical within all \( r_{\text{vir}} \), and (4) X-ray line emission is ignored. Although reasonable, these assumptions are not perfectly satisfied. For example, the gas variables within the accretion shock \( r_{\text{sh}} \), which typically occurs very close to the virial radius, are not expected to be strictly homologous in \( r/r_{\text{vir}} \), and furthermore, the halo concentration varies somewhat with \( M_{\text{vir}} \). Nongravitational heating of the gas in excess of that received in the accretion shock can cause the mass fraction in gas to vary with virial mass. Line emission becomes important at \( T \lesssim 10^7 \) K, relevant for galaxy groups. At these low temperatures the radiative cooling coefficient \( A(T, Z = 0.4) \propto T^2 \), with \( p \lesssim 0 \), which flattens the \( L-T \) slope to at least \( L \propto T^{3/2} \). Finally, the NFW halo for a given virial mass and cosmology represents a computational measure of scatter for dark halos of the same \( M_{\text{vir}} \). Bullock et al. (2001) find a 1 \( \sigma \) scatter of \( \sim 50\% \) in the concentration parameter.

We consider four levels of preheating for each of the three virial masses. This is done by arbitrarily raising the temperature to \( T_n \) everywhere in the \( \Lambda \)CDM flow at time \( t_n = 0.5 \) Gyr (redshift \( z = 9 \)) when the cosmic baryonic density is \( \rho_h = 3.61 \times 10^{-28} \) g cm\(^{-3} \). For comparison with other recent discussions of the preheating hypothesis, we also reset the temperature and density to be everywhere constant at time \( t_n \). By this time the NFW dark matter halos have masses constant at \( 6 \times 10^{12}, 4 \times 10^{13} \), and \( 10^{14} M_\odot \) for groups, poor clusters, and clusters, respectively. Gas that had already entered the dark halos at time \( t_n \) is spread uniformly with the rest of the gas at the reset. The heat supplied to the gas at these early times places the universal gas on an adiabat that can be represented with an entropy factor

\[
K_{34} \equiv 10^{-34} \frac{kT_n}{\mu m_p \rho_h^{3/4}} = 2.3 \times 10^{-8} \frac{T_n}{0.31 T_{\text{h, keV}}} \ ,
\]

as defined by Tozzi & Norman (2001), which is evaluated at time \( t_n \). The corresponding entropy factor defined by Ponman et al. (1999) is

\[
S \equiv \frac{T}{n_e^{2/3}} = 985 K_{34} \text{ keV cm}^2 \, \text{g}^{-1} \ .
\]

The four levels of heating we consider (\( T_n = 10^4, 5 \times 10^4, 10^5 \), and \( 3 \times 10^7 \) K, corresponding to 0.0013, 0.65, 1.3, and 3.9 keV per particle) are numerically characterized by 1–4 in our model nomenclature and correspond to entropies \( K_{34} = 2.55 \times 10^{-4}, 0.127, 0.255, \) and 0.764, respectively. The three virial masses are referred to as “g,” “p,” and “c” for group, poor cluster, and cluster, respectively. For example, model ADg1 refers to an adiabatic model for gas flow in a galaxy group potential in which the temperature is set to \( T_n = 10^4 \) K at \( t_n \). In all model calculations, as the gas evolves, we never allow its temperature to drop below \( 10^4 \) K, as would be expected in a photoionized intergalactic medium (IGM).

Previous discussions of preheating have not emphasized the possibly important role of Compton cooling against the cosmic background radiation. After preheating, the electron gas is Compton cooled but the proton temperature \( T_p \) remains unchanged until equipartition is established by Coloumb interactions. To explore this, we assumed \( T_n = 10^7 \) K for both electrons and protons at \( t_n = 0.5 \) Gyr, and integrated equations for \( T_p(t) \) and \( T_n(t) \) in our assumed \( \Lambda \)CDM universe, allowing for Compton cooling, equipartition, and normal expansion cooling \( dT_{\text{exp}}/dz = 2T_{\text{exp}}/(1 + z) \). While the electrons rapidly lose half of their thermal energy relative to \( T_{\text{exp}} \) by \( (t, z) = (0.64 \text{ Gyr}, 7.7), T_p = 0.57T_{\text{exp}} \) occurs at a much later time, \( (t, z) = (3.1 \text{ Gyr}, 2.0) \). By the latter time the proton temperature \( T_p = 4.5 \times 10^5 \) K is much less than halo virial temperatures of interest and has negligible thermal energy as it enters the accretion shock. Although our computed accretion flows are not generally influenced by Compton cooling, it should be noted that the epoch of (universal) preheating cannot be much earlier than \( t_n \approx 0.5 \) Gyr or the gas would rapidly cool and may also leave an observable perturbation on the cosmic microwave background. With this potential difficulty in mind, we shall assume \( t_n = 0.5 \) Gyr in most of our calculations and consider a single-temperature gas.

3. GASDYNAMIC MODELS FOR GROUPS AND CLUSTERS

3.1. Adiabatic Models

In our “adiabatic” (AD) models the entropy only increases when the gas is shocked. By far most of the entropy increase occurs when the gas passes through the accretion shock as it enters the NFW halo, \( r_{\text{sh}} \approx r_{\text{vir}} \), and encounters nearly stationary gas that arrived earlier. The postshock temperature is comparable to the halo virial temperature

\[
T_{\text{vir}} \approx \gamma \frac{\mu m_p G M_{\text{vir}}}{k T_{\text{vir}}} \approx 2.97 \times 10^6 \left( \frac{M_{\text{vir}}}{10^{13} M_\odot} \right)^{2/3} \text{K} \ ,
\]

where \( \mu = 0.61 \) is the mean molecular weight and \( \gamma \approx 0.5 \) from Eke et al. (1998). The current virial temperatures for the three dark halos we consider are \( T_{\text{vir}} \approx 8.1 \times 10^6, 2.3 \times 10^7 \), and \( 7.2 \times 10^7 \) K. If the temperature of gas entering the dark halo \( T_{\text{pre}} \) is comparable to (or significantly exceeds) \( T_{\text{vir}} \), then the accretion shock weakens and gas flows nearly adiabatically into the halo, preserving its entropy. The temperature of gas entering the accretion shock at the present time \( (t_n = 13 \text{ Gyr}) \) has cooled by adiabatic expansion to \( T_{\text{pre}}(t_n) = T_n (\rho_{\text{pre}}/\rho_h)^{2/3} = 0.01 T_n \) or \( 10^4 \) K, whichever is larger. In any case, a shock must always propagate away from the origin (where the flow velocity vanishes), even if the converging flow there is subsonic. Finally, for models with the least amount of IGM preheating (AD1), spurious shocks may develop just after time \( t_n \) as gas with subviral temperatures flows into the dark halo.

3.1.1. Adiabatic Models in the L-T Diagram

Bolometric X-ray luminosities and emission-weighted mean temperatures for 12 adiabatic models (three and four \( T_n \)) at time \( t_n = 13 \) Gyr are shown with the obser-
vational data in Figure 1a. The gas has been heated to \( T_h \)
and reset to spatial uniformity at \( t_h = 0.5 \) Gyr. As the virial mass
increases from groups to clusters (filled circles→filled squares→filled triangles), the computed results follow the
general trend of the observations, even for these simple
adiabatic models. For each virial mass the final luminosity is
progressively lower as the amount of assumed preheating
increases, AD1→AD4. This is expected since with increased
preheating the entropy of the gas that enters the halo at
early times may exceed the entropy that would have been
achieved in the accretion shock. As the entropy at the center
of the flow increases, the gas density and X-ray emissivity
are reduced, corresponding to lower \( L \) in Figure 1a. With
increasing virial mass, each cluster of four models (1→4)
becomes more compact in Figure 1a since \( \frac{r_{ac}}{T_{vir}} \) is
satisfied for the largest \( M_{vir} \), even with the maximum
amount of preheating. Further details of the AD models
are listed in Table 1.

Although the adiabatic series of models does not lose
energy by radiation, to compute the luminosities plotted in
Figure 1a, it is necessary to assume that they do in fact
radiate with emissivity \( \propto \rho T^3 \). The cooling coefficient
\( \Lambda(T, Z) \) that we use (taken from Sutherland & Dopita 1993)
corresponds to abundance \( Z = 0.4 \) (solar meteoritic) for
which \( \Lambda(T) \) reaches a minimum at \( T \approx 1 \) keV because of
increasing line emission at lower temperatures.

Finally, the results shown in Figure 1a are sensitive to the
time at which the reset is made and are very different if the
reset is ignored altogether. For example, if \( t_h = 2 \) instead of
0.5 Gyr, the temperatures of the final ADg models are
relatively unchanged, but the luminosities are very much
lower than those in Figure 1a: \( \log (L/10^{45}) = -2.48 \) for ADg1
and \( -5.17 \) for ADg4. When the reset occurs at lower red-
shifts, more gas must be removed from the halos and the
subsequent accretion in the \( \Lambda CDM \) universe is insufficient
on reestablish the present-day X-ray luminosity. Therefore,
explanations for both the amount of universal preheating
and the epoch at which it is applied are required in external
heating scenarios. If the reset is completely ignored, values
of \( L \) are increased enormously. For example, \( L \gtrsim 10^{46} \) ergs
\( \text{s}^{-1} \) for model ADg1nr ("nr" signifies no reset), as shown in
Table 1. These no-reset groups have X-ray luminosities
comparable with the richest clusters observed. The reason
for this is that dense, low-entropy gas flowed into the group
potential before time \( t_h \) and, if not removed, must remain
there in the absence of reset. The very dense central gas
\( n_e \sim 100 \) cm\(^{-3} \) that entered the halo at very high redshifts
accounts for the enormous \( L \) of AD groups without reset. In
more realistic models this gas would have radiated its
energy away and formed into stars.

3.1.2. Adiabatic Models in the S-T Diagram

Ponman et al. (1999) and Lloyd-Davies et al. (2000) have
emphasized a related non-self-similar deviation of galaxy
group observations in the entropy-temperature plane. They
compare the emission-weighted mean temperature \( T \) to the
entropy factor evaluated at approx-
imately \( 0.1 \) \( T_{vir} \) evaluated at \( 0.1 \) \( T_{vir} \) approx-
imately the outer extent of current observations. The same
idealized, self-similar group-cluster models that correspond
to \( L \propto T^2 \) would appear as \( S_{0.1} \propto T \) in Figure 2a.
However, it is seen that the entropy observed in groups
generally exceeds the \( S \propto T \) variation when extrapolated
from observations of rich clusters. Nevertheless, the devi-
ration from similarity is less robust in the \( S-T \) plane than in
the \( L-T \) diagram since \( S_{0.1} \) refers to a single point in the observed or computed entropy distribution and,
for the observations, also requires an estimate of the
virial radius. The observational errors are substantial and
can be found in the papers cited above.

Values for \( S_{0.1} \) from the computed adiabatic models are
plotted as open circles in Figure 2a. Entropies \( S_{0.1} \) for
models AD4 with the highest level of preheating, shown
with the largest circles, depend weakly on \( M_{vir} \) since the
entropy acquired from preheating dominates that from
shocks. As the preheating at time \( t_h \) is reduced, \( S_{0.1} \)
decreases with \( M_{vir} \), approaching the expected \( S \propto T \). However, \( S_{0.1} \) for the least heated models, ADpc1 and
ADc1, exceeds the entropy for ADpc and ADc models that
received more preheating. The source of this discrepancy
can be traced to postshock irregularities in the entropy
profile \( S(r) \) created by weak shocks produced during the
transient adjustment following the reset time \( t_h \). Immedi-
ately after reset, cosmically inflowing gas outside the virial
radius encounters stationary gas within. This gives rise to
both outward and inward propagating shocks. The latter
shock confronts a third outward moving shock produced as
gas of uniform (post-reset) density falls toward the origin,
reflecting as a shock. The local increase in entropy depends
on the local strength of each shock that passes through.
These artifacts of the reset assumption imprint long-lived
entropy irregularities in the gas. The effect of these transient
shocks is much reduced in models with more preheating
since the sound speed is larger and shocks are greatly
reduced in strength.

The resulting fluctuations in \( S(r) \) are evident in Figure 3,
where we plot entropy profiles for groups and clusters (ADg
and ADc) at the present time. For each \( S(r) \) profile there are
several regions of interest: the relatively flat cosmic inflow

\[ \text{Table 1} \]

| Model     | \( \langle T \rangle^a \) (keV) | \( \log L^a \) (ergs s\(^{-1} \)) | \( \log S(0.1r_{vir})^b \) (keV cm\(^3\)) | \( f_{sl}(r_{vir})^c \) |
|-----------|-------------------------------|---------------------------------|---------------------------------|-----------------|
| ADg1      | 0.814                         | 43.55                           | 2.02                            | 0.0918          |
| ADg2      | 0.906                         | 43.12                           | 2.15                            | 0.0900          |
| ADg3      | 0.853                         | 42.86                           | 2.43                            | 0.0856          |
| ADg4      | 0.843                         | 41.94                           | 2.91                            | 0.0420          |
| ADpc1     | 1.89                          | 44.19                           | 2.55                            | 0.0931          |
| ADpc2     | 2.44                          | 43.95                           | 2.42                            | 0.0916          |
| ADpc3     | 2.46                          | 43.83                           | 2.51                            | 0.0899          |
| ADpc4     | 2.36                          | 43.41                           | 2.91                            | 0.0811          |
| ADc1      | 6.13                          | 44.99                           | 2.87                            | 0.0907          |
| ADc2      | 6.72                          | 44.91                           | 2.68                            | 0.0902          |
| ADc3      | 6.96                          | 44.85                           | 2.82                            | 0.0997          |
| ADc4      | 7.20                          | 44.68                           | 2.97                            | 0.0877          |
| ADg1nr    | 0.392                         | 46.14                           | 1.83                            | 0.121           |
| ADg4nr    | 0.425                         | 44.76                           | 1.85                            | 0.068           |
| ADpc1nr   | 0.760                         | 46.41                           | 1.63                            | 0.121           |
| ADpc4nr   | 0.908                         | 45.47                           | 2.22                            | 0.100           |
| ADc1nr    | 1.714                         | 46.78                           | 2.44                            | 0.117           |
| ADc4nr    | 2.399                         | 46.14                           | 2.81                            | 0.114           |

* Nomenclature: g, pc, and c represent group, poor cluster, and
center potentials, respectively; 1 indicates no preheating; 3 and 4 rep-
resent increasing levels of preheating; and nr indicates no reset.

1 Emission-weighted temperature within \( r_{vir} = 0.088 \), 1.47, and 2.63
Mpc for group, poor cluster, and cluster, respectively.

2 Bolometric X-ray luminosity within \( r_{vir} \).

3 Entropy factor at 0.1 \( r_{vir} \).

4 Baryon fraction in hot gas within \( r_{vir} \).
Trinchieri, Fabbiano, & Kim (1997). GAg panel shows the observed entropy profile for group NGC 2563 from models refer to calculated profiles without reset. The dot-dashed line in the long-dashed lines, respectively. The thick dotted lines for ADg and ADc 1 respectively. The amount of heating described in the text with the nomenclature radiative cooling (CO), mass dropout (DO), and galaxy formation (GA) in the ADg2 solutions in Figure 3. The entire entropy profile for model ADg4 is almost constant. However, converging subsonic flow must always produce an outward-propagating shock since the flow velocity is assumed to vanish at the origin. The strength of this shock, which increases with virial mass \( M_{\text{vir}} \), can produce central regions with \( ds/dr < 0 \), as in the ADc1–ACc4 models in Figure 3. Since these small inner regions are convectively unstable, the entropy would also become uniform in a more realistic three-dimensional calculation.

The choices of \( S_{0,1} \) and emission-averaged temperature \( T \) in the \( S-T \) diagram are determined by the realities of observational limitations, but they are probably not the best coordinates to test deviations from similarity. These inner flow regions near 0.1\( r_{\text{vir}} \) are also subject to computational difficulties from ancient shocks as apparent in the AD1 and AD1nr entropy profiles in Figure 3. Even if the cosmic gas were perfectly adiabatic between shocks, we expect that the violent events that accompany the earliest mergers would disturb the entropy of the central regions near 0.1\( r_{\text{vir}} \), which in our models passed through the accretion shock at \( \sim 1 \) Gyr (redshift \( z \sim 5 \)). The emission-weighted temperatures also heavily favor the same dense inner region sensitive to these early perturbations. Aside from the entropy fluctuations apparent in the inner flow \( r \leq 0.1 r_{\text{vir}} \) in Figure 3, our calculations are quite accurate elsewhere. This is evident in Figure 4, where we plot entropies and temperatures that are mass-averaged values within the accretion shock. In these \( S-T \) coordinates the unheated AD1 models lie exactly along the similarity variation \( S \propto T \). Small deviations from this relation occur with increased preheating and smaller virial masses, just as one would expect.

When the reset assumption is not made, as in the “nr” solutions listed in Table 1 and ADg1nr and ADc1nr plotted in Figure 3, the entropy in the inner postshock flow is very much lower. In these flows, gas at \( 10^4 \) K that entered the halo at high redshifts, when the cosmic flow was dense, had very low entropy. The high density of this gas is maintained during its evolution. In addition, the emission-averaged temperatures of the “nr” solutions are much too low, biased by the central regions. This is still true even if all the gas is heated (without reset) to \( 3 \times 10^7 \) K at time \( t_s = 0.5 \) Gyr, as shown in the ADg4nr, ADp4nr, and ADc4nr results in Table 1. Some irregularities in the entropy profile in Figure 3 for the ADc1nr flow arise from weak shocks produced at very early times \( t_s \) when the dark halo mass distribution changed to an NFW profile.

Clearly, adiabatic models without reset are unacceptable since their X-ray luminosities are excessive and they have not cooled or formed into stars and galaxies. The high luminosities of no-reset flows are related to the strong high-redshift emission from groups that would violate the soft X-ray background, as discussed by Pen (1999) and WFN01. However, adiabatic solutions with the reset condition are also problematic because the time \( t_s \) of universal heating must be carefully orchestrated for agreement with observed X-ray luminosities of galaxy groups. Nevertheless, AD flows provide a useful reference for more detailed externally heated flows. Moreover, the entropy profiles \( S(r) \) for the AD solutions in Figure 3 share many of the same features with more realistic externally preheated models discussed below.

**3.2. Models with Radiative Cooling**

This series of gasdynamic models, described with the prefix CO, is similar to the adiabatic models except that...
we now include radiative emission according to the Sutherland-Dopita (1993) cooling coefficient $\Lambda(T, Z = 0.4)$. When the gas cools at the center of the flow, we allow it to accumulate there, producing a point mass gravitational potential similar to a giant black hole. At time $t_h = 0.5$ Gyr we reset the gas temperature and density to be spatially uniform and apply the preheating. These assumptions are essentially identical to those made by Tozzi & Norman (2001). The entropy decrease due to radiative losses has little effect on the temperature profile since for hydrostatic support the gas temperature must always be close to $T_{\text{in}}$, i.e., $T \propto M(r)/r$ and $M(r)$ is approximately proportional to $r$. However, close to the central concentration of cooled gas, $M(r)$ is nearly constant and the temperature increases toward the origin as $T \propto 1/r$. The locally higher temperatures in this dense central gas can influence the global emission-weighted temperature profile of the group or cluster.

In some models with radiative cooling hot gas containing an appreciable amount of specific enthalpy and kinetic energy flows into the central numerical zone. Since this gas must ultimately radiate this energy producing X-rays, the central region contributes an additional X-ray luminosity given by

$$L_{\text{core}} = 4\pi r_1^2 \rho_1 u_1 \left( \frac{u_1^2}{2} + \frac{5kT_1}{2m_p} \right),$$

where the subscript 1 refers to quantities evaluated at the radius $r_1 = 150$ pc of the innermost numerical grid. This estimated correction to the total luminosity can be quite large, often exceeding $L$ from the rest of the cooling flow. Since X-ray observations of cores of cooling flows do not reveal strong, high-temperature thermal point sources, the assumption that the gas cools only at the center of the flow is unrealistic.

3.2.1. Cooling Models in the L-T Diagram

$L$ and the emission-weighted $T$ for the CO (radiative cooling) models are illustrated in Figure 1b. The results for cluster mass halos (COc, filled triangles) are similar to the adiabatic models with reset, as a result of the inefficiency of radiative cooling in these hot, low-density halos. In gas flows with the largest preheating (COg3, COg4, COpc3, COpc4, and COe4) none of the baryonic gas cools in $t_h < t < t_f$, as shown in Table 2. These strongly preheated models fit the observations in Figure 1b quite well even for low-luminosity groups. However, the remaining cooling flow models with less preheating are currently accumulating uncooled gas in the origin. As shown in Table 2, for these flows the concentrated X-ray emission from the central zone $L_{\text{core}}$ is $3-13$ times that from the rest of the flow within the virial radius. In addition, the colossal masses in the central baryonic singularity, $\gtrsim 6 \times 10^{11} M_\odot$, are similar to those of massive galaxies. Clearly, none of these weakly preheated models are physically acceptable.

Another distinctive feature of the CO series of calculations is the appearance of galactic drips at early times ($\sim 1$ Gyr) for clusters and poor clusters and slightly later ($\sim 5$ Gyr) for groups. Galactic drips are dense, narrow cooling waves that begin in the outer halo and proceed inward, crossing the cooling flow in $\lesssim 1$ Gyr. The drips discussed by Mathews (1997) actually lose mass en route by local cooling. However, drips in the CO models continue to the origin before cooling, so they are more massive and move faster than the drips discussed by Mathews (1997). The cooling evolution of spherically symmetric drips depends somewhat on the numerical resolution. Spherical drip waves are an artifact of spherical symmetry in which the inherent three-dimensional character of Rayleigh-Taylor instabilities is suppressed. Although drip waves have a physically plausible origin and may well occur in cooling flows, the wave fronts are unlikely to be globally spherical and their multidimensional evolution is currently uncertain. Drips occur only in CO models with little or no preheating.
approximate profiles computed by Tozzi & Norman (2001), these entropy profiles are in good agreement with the

... as drips arrive at the origin, the mass of cooled gas there in(

... most two drip waves occur in each of these models. As drips

... (e.g., COg1, COc2, COpg1, and COc1), and only one or at

... most two drip waves occur in each of these models. After a drip wave has passed through gas at the center of the flow, its entropy increases because the drip waves become supersonic in \( r \lesssim 0.1 r_{\text{vir}} \). The postdrip gas density is also lower since the drip wave transfers mass to the center. These factors contribute somewhat to the low \( L \) for the COg1 model in Figure 1b. Both density and temperature gradients in the inner flow \( (r \lesssim 0.1 r_{\text{vir}}) \) are considerably flattened following the passage of drip waves. Since drips typically begin at \( r \approx 0.3 r_{\text{vir}} \) and move inward, they have little influence on the outer ~70% of the cooling flows.

3.2.2. Entropy of Cooling Models and No-Reset Models

Entropy factors \( S = T/n_e^{2/3} \) (evaluated at \( r = r_{\text{vir}}/10 \)) for the CO models are plotted against emission-averaged temperatures for groups and clusters in Figure 2b. As the amount of preheating is reduced, the results approach the expected \( S \propto T \) variation, but the entropy in these weakly preheated flows is increased by the passage of drip waves and shocks produced by transient flows following reset. Because of these complications, the entropy \( S_{0.1} \) computed at small radii is uncertain and the agreement with observations in Figure 2b is poor. The globally mass-averaged entropy and temperature satisfy the similarity condition \( S \propto T \) very well (Fig. 4b) but cannot be easily compared with currently available observations.

In Figure 3 we show the computed entropy profiles \( S(r) \) at \( t_a = 13 \) Gyr for group and cluster CO models. In general these entropy profiles are in good agreement with the approximate profiles computed by Tozzi & Norman (2001), but models that experienced drips (e.g., COg1) have higher central entropies and gas temperatures in \( r \lesssim 0.1 r_{\text{vir}} \) as a result of the influence of drip waves. For the most strongly preheated models the entropy is high everywhere. In less strongly preheated flows the entropy is seen to decrease slightly as the gas approaches the accretion shock; this occurs because the preshock flow is isothermal at \( T_{\text{pre}} = 10^4 \) K, as explained earlier. The accretion shock (at all times) occurs very close to the virial radius: \( \log r_{\text{vir}} \) is 2.94 and 3.42 for groups and clusters, respectively. The entropy just behind the strong accretion shock increases with virial mass. As with the AD solutions, the positive entropy gradient in the immediate postshock flow, \( S \propto (r/r_{\text{vir}})^p \) with \( p \approx 1 \), is due to the increasing strength of the accretion shock with cosmic time (Tozzi & Norman 2001). In the inner flow region, \( r \lesssim 0.1 r_{\text{vir}} \), the entropy variation \( S(r) \) depends on several competing processes. The central entropy is increased by drip-induced shocks (COg1) or (in COg3 and COg4) by outward-propagating shocks generated by the initial nearly adiabatic flow of uniform postreset gas into the origin. In the latter case \( dS/dr < 0 \) so the (small mass of) gas very close to the center of the flow would be convectively unstable. Radiation losses from the dense central regions lower the central entropy of CO models below the corresponding AD model, although the effect of this can be reversed by drips (COg1, COc1, and COc2).

We have also computed representative CO flows with no-reset, COnr models, in which the gas acquired by the dark halo before \( t_b \) is not removed. In these exploratory calculations the temperature of CO4nr models is increased by \( 3 \times 10^7 \) K at \( t_a \) but CO1nr models receive no additional heating. The unsatisfactory results of these models are listed in Table 2. All of these “nr” flows suffer from early intense

| Model     | \( \langle T \rangle^b \) (keV) | \( \log L^d \) (ergs s\(^{-1}\)) | \( \log S(0.1r_{\text{vir}})^e \) (keV cm\(^{-3}\)) | \( f_{\text{d}}(r_{\text{vir}})^f \) | \( \log M_{\text{cold}}^i \) (M\(_{\odot}\)) |
|-----------|-----------------|-----------------|-----------------|----------------|----------------|
| COg1      | 1.10            | 43.67(44.55)    | 1.76            | 0.083(0.095)   | 11.77          |
| COg2      | 1.32            | 43.82(44.62)    | 1.81            | 0.080(0.096)   | 11.59          |
| COg3      | 0.886           | 43.11           | 2.21            | 0.092(0.092)   | ...            |
| COg4      | 0.831           | 42.00           | 2.87            | 0.045(0.045)   | ...            |
| COpc1     | 2.45            | 44.21(44.80)    | 2.15            | 0.09(0.094)    | 11.94          |
| COpc2     | 2.39            | 44.24(44.90)    | 2.28            | 0.091(0.094)   | 11.80          |
| COpc3     | 2.32            | 44.10           | 2.34            | 0.092(0.092)   | ...            |
| COpc4     | 2.38            | 43.47           | 2.85            | 0.082(0.082)   | ...            |
| COc1      | 7.12            | 44.87(45.40)    | 2.78            | 0.088(0.091)   | 12.55          |
| COc2      | 7.14            | 44.92(46.04)    | 2.89            | 0.088(0.091)   | 12.53          |
| COc3      | 6.15            | 45.11(45.90)    | 2.91            | 0.089(0.090)   | 12.16          |
| COc4      | 7.12            | 44.77           | 2.90            | 0.088(0.088)   | ...            |
| COc1nr    | 2.58            | 43.00(45.35)    | 2.40            | 0.065(0.126)   | 12.48          |
| COc4nr    | 1.28            | 42.28(44.10)    | 2.53            | 0.047(0.079)   | 12.16          |
| COc1nr    | 14.93           | 44.91(47.69)    | 2.94            | 0.085(0.118)   | 13.60          |
| COc4nr    | 8.54            | 44.87(46.93)    | 2.97            | 0.092(0.114)   | 13.41          |

\( ^a \) Nomenclature: \( g, pc, \) and \( c \) represent group, poor cluster, and cluster potentials, respectively; \( 1 \) indicates no preheating; \( 3 \) and \( 4 \) represent increasing levels of preheating; and \( nr \) indicates no reset.

\( ^b \) Emission-weighted temperature within \( r_{\text{vir}} = 0.88, 1.47, \) and 2.63 Mpc for group, poor cluster, and cluster, respectively.

\( ^c \) Bolometric X-ray luminosity within \( r_{\text{vir}} \); values of \( (L + L_{\text{cool}}) \) are shown in parentheses when gas cools in the central zone.

\( ^d \) Entropy factor at \( 0.1 r_{\text{vir}} \).

\( ^e \) Baryon fraction in hot gas within the total baryon fraction including dropout mass is shown in parentheses.

\( ^f \) Mass cooled at \( r = 0 \).
radiative (over)cooling, producing baryon mass singularities about 10 times larger than those of the AD models. As a result, the X-ray luminosity is currently totally dominated by emission from the core, $L_{\text{core}} \gg L$. The unrealistic nature of these CO models without reset strongly argues for star formation and supernova heating that drives gas out of small dark halos, locally raising its entropy.

In summary, our solutions for the CO models are in good agreement with those of Tozzi & Norman (2001), particularly in the postshock entropy profiles shown in Figure 3. However, our gasdynamical calculations have illustrated some additional features: the presence of drip waves, the concentrated X-ray emission from the baryonic singularity, a density enhancement as the gas approaches the accretion shock (Tozzi, Scharf, & Norman 2000), and shock heating at the origin. Our CO results depend critically on the assumption used by many authors (e.g., Kaiser 1991; Cavaliere et al. 1997; Balogh et al. 1999; Wu, Fabian, & Nulsen 1998, 2000; Tozzi & Norman 2001) that the baryonic density and temperature are nearly uniform at the moment of preheating $t_p$ before gas flows into the dark halo potentials. In fact, however, baryonic gas is already concentrated in the dark halos at time $t_p$, and the most natural means of removing it is with supernova-driven winds.

### 3.3. Mass Dropout Models

The DO calculations are identical to the CO models except that the cooling flows are assumed to be inhomogeneous, containing entropy (or magnetic) irregularities that allow the gas to cool ("dropout") at large distances from the origin. These DO models are an improvement over the CO models in which baryonic mass singularities form at the origin having masses that are much greater than the masses of black holes observed in luminous elliptical galaxies. The CO models also produce extremely bright central X-ray sources that are not observed. Although the details of mass dropout are poorly understood, spatially distributed radiative cooling is required in elliptical galaxy cooling flows. For example, the masses of central black holes in elliptical galaxies are about 10 times smaller than the total amount of diffuse cooling flow gas that has cooled over a Hubble time. In addition, the X-ray isophotes of cooling flow gas in rotating galaxies do not exhibit rotational flattening; this can be understood if angular momentum is being lost by distributed radiative cooling (Brighenti & Mathews 2000a, 2000b).

The local cooling dropout rate in an inhomogeneous cooling flow depends on the amplitude distribution of the entropy or magnetic inhomogeneities, which cannot be directly observed or derived ab initio. For a simple heuristic representation of mass dropout it is customary to introduce a sink term in the equation of continuity of the form $-q(r)\rho/\tau_{\text{p0}} \propto \rho^2$, where $\tau_{\text{p0}} = 5\rho_k T/2\mu \lambda$ is the time for gas to cool locally by radiative losses at constant pressure. With this term the elliptical galaxy X-ray surface brightness distributions more nearly resemble those observed and the dynamical mass-to-light ratios are not greatly disturbed (e.g., Sarazin & Ashe 1989; Brighenti & Mathews 2000a). Successful models require that the dimensionless dropout parameter $q$ is close to unity. We assume that $q = 1$ in the DO models computed here and that it applies only to hot gas $T > 10^5$ K. The influence of galactic drips is lessened in the DO models but not entirely eliminated; their amplitude and velocity are reduced as gas cools in the wave and is locally deposited, similar to the drips described by Mathews (1997). Since we view the DO models as a variant of the CO models, we continue to reset the gas temperature and density at time $t_p$. Flow irregularities introduced by the reset tend to be lessened by mass dropout in the DO models. Finally, we note that when $q = 1$, about half of the bolometric X-ray luminosity is produced by the cooling regions (Brighenti & Mathews 1998).

An important beneficial effect of the distributed dropout models is that they do not produce the unrealistic central baryonic mass concentrations that occur in the CO models. Instead, the cooled baryons are assumed to remain at approximately the same radius at which the cooling dropout occurs. This would be expected if the cooled gas forms into stars that spend most of their time orbiting near the radius where they formed. As gas cools according to the $q = 1$ sink term over many gigayears, an extended region of stars forms from the cooling dropout (Nulsen & Fabian 1995, 1997). The density structure of the dropout stellar population has a remarkable resemblance to a de Vaucouleurs profile, particularly at early times, $t \sim 2$ Gyr. For the DO models discussed here, the dropout term is applied to the baryonic gas within the current virial radius; at earlier times only a very small amount of dropout occurs in the low-density preshock cosmological flow.

#### 3.3.1. Dropout Models in the L-T Diagram

The results of the spatially distributed dropout (DO) models in the $L-T$ plane are shown in Figure 1c. The DO models exhibit many of the same trends as the CO models in Figure 1b, but the cooled baryons are less concentrated so the X-ray surface brightness distribution is also less centrally concentrated. For each of the three virial masses we consider, the total mass of cooled gas in the DO models $M_{\text{cool}}$ within the current virial radius is insensitive to the amount of preheating, as shown in Table 3. The filled triangles in Figure 1c, corresponding to models with cluster mass halos, DOc, are in excellent agreement with observations and are largely unaffected by the various levels of preheating. The poor cluster solutions lie above the Arnaud-Evrard (1999) observations, but recall that their sample favored clusters with weak cooling flows that are hotter and therefore appear systematically underluminous in the $L-T$ plot. In addition, Arnaud & Evrard (1999) did not extrapolate the observed X-ray luminosities to the virial radius. For both groups and poor clusters the luminosity decreases as the amount of preheating increases. The emission-weighted temperatures also decrease slightly as DO1–DO4 since the more strongly preheated models produce less total mass dropout and the lowered gravity of this dropout mass requires lower gas temperatures for hydrostatic support.

Overall, the results in Figure 1c for group, poor cluster, and rich cluster DO models are in good agreement with the observations, particularly if the preheating is strong. Models DOg1–DOg3, with little or no preheating, clearly lie above the group observations of Helsdon & Ponman (2000a). The most consistent models, when compared to the observations, are DOg4, DOpC4, and DOc4. While this clearly supports the argument for cosmic preheating that has been widely discussed, we note that the amount of preheating required cannot be explained solely by supernova heating associated with normal star formation (e.g., Loevenstein 2000). The timing is also wrong since most galactic stars are thought to have formed at redshifts much less than
$z_h = 9$, corresponding to the epoch of preheating $t_h = 0.5$ Gyr.

Since the DOg4 model agrees so well with typical Heldson-Ponman (2000a) groups in Figure 1c, it is interesting to estimate the amount of preheating that would be required to raise the entropy to the DOg4 (preshock) level at various redshifts. The amount of heating required to reach the same entropy of the DOg4 model is $3.9, 0.92, 0.59, 0.33,$ and $0.19$ keV per particle if the heating occurred at redshift $z = 9, 4, 3, 2$, and $1$, respectively. If about $0.1$ of all baryons formed into stars ($\Omega_b/\Omega_{\text{baryon}} = 0.09$; Fukugita et al. 1998) with a Salpeter IMF (as discussed above), this would generate only about $0.19$ keV per particle. The required level of cosmic entropy in model DOg4 (Fig. 1c) would be (just) consistent with supernova heating and normal star formation if most stars formed at redshifts $z \lesssim 1$. Such recent supernova heating is clearly inconsistent with our knowledge that most stars in group-dominant early-type galaxies were formed well before redshift $z = 1$. Therefore, if the preheating is cosmic and universal, it must have a non-stellar (AGN?) origin or be produced by (Population III?) stars that have no surviving IMF counterparts today. In addition, the preheating in our models occurred at $t_h = 0.5$ Gyr before very much gas entered the dark potential (e.g., WFN01); if the heating by stars occurred at later times, much luminous gas would have entered the dark potentials, in possible conflict with the observed X-ray background.

### 3.3.2. Entropy, Cooled Gas, and No-Reset DO Models

The behavior of DO models at time $t_h = 13$ Gyr in the $S$-$T$ plot is illustrated in Figure 2c. For each virial mass the entropy decreases with decreasing amounts of preheating. However, the DOg models that fit best in the $S$-$T$ plot, DOg1 and DOg2, agree less well with observations in the $L$-$T$ plot (Fig. 1c), the best compromise model may be DOg3. However, we note again that the $S$-$T$ plot (with $S$ and $T$ evaluated at $r = 0.1r_{\text{vir}}$) is a less accurate indicator of the amount of preheating than the more globally representative $S$-$T$ plot in Figure 4c or the $L$-$T$ plot (Fig. 1c).

Figure 3 shows the final entropy profiles in the group and cluster DO models. Many of the same features shown for the CO models appear again, but there are some significant differences, particularly in the inner regions $r \lesssim 0.1r_{\text{vir}}$. Most of these differences can be understood in terms of the gas velocity. In the CO solutions, the gas accelerates within $0.1r_{\text{vir}}$ as it approaches the central mass concentration, so less energy is radiated in this region and the entropy profiles become flat. By contrast, in the DO solutions the central gas velocity is slowed by mass dropout and a much larger fraction of its entropy is radiated away. Dropout causes subsonic flows to move even slower (Sarazin & Ashe 1989; Brighenti & Mathews 2000). This explains the continued decrease in $S(r)$ in many of the DO models as gas flows from $\sim 0.1r_{\text{vir}}$ to the origin. For the DOg models this region would be dominated by the central elliptical galaxy. Note that the group flow without preheating, DOg1, contains a low-entropy drip wave at log $r = 2$, which is moving slowly inward, but it has no strong influence on the solution elsewhere. Radiation losses are less important in dropout flows with the largest preheating, DOg3, DOg4, and DOc4, and the entropy remains more nearly constant throughout the inner flow.

| Model    | $\langle T \rangle^a$ (keV) | $\log L^b$ (ergs s$^{-1}$) | $\log S(0.1r_{\text{vir}})^c$ (keV cm$^2$) | $f_d(0.1r_{\text{vir}})^d$ | $\log M_{\text{cold}}^e$ ($M_{\odot}$) |
|----------|-----------------------------|-----------------------------|------------------------------------------|-----------------------------|----------------------------------------|
| DOg1     | 0.933                       | 43.61                       | 1.99                                     | 0.072(0.114)                | 12.31                                  |
| DOg2     | 0.941                       | 43.61                       | 2.05                                     | 0.072(0.115)                | 12.35                                  |
| DOg3     | 0.795                       | 43.27                       | 2.32                                     | 0.081(0.111)                | 12.17                                  |
| DOg4     | 0.743                       | 42.34                       | 2.89                                     | 0.045(0.067)                | 11.98                                  |
| DOc1     | 2.27                        | 44.35                       | 2.25                                     | 0.084(0.106)                | 12.68                                  |
| DOc2     | 2.55                        | 44.36                       | 2.43                                     | 0.077(0.107)                | 12.81                                  |
| DOc3     | 2.02                        | 44.21                       | 2.47                                     | 0.084(0.105)                | 12.64                                  |
| DOc4     | 1.89                        | 43.76                       | 2.97                                     | 0.085(0.098)                | 13.17                                  |
| DOc1nr   | 1.24                        | 45.59                       | 1.98                                     | 0.066(0.123)                | 12.45                                  |
| DOc2nr   | 1.54                        | 43.89                       | 1.95                                     | 0.069(0.129)                | 12.48                                  |
| DOc3nr   | 1.29                        | 43.49                       | 2.24                                     | 0.083(0.125)                | 12.33                                  |
| DOc4nr   | 1.43                        | 43.31                       | 2.25                                     | 0.050(0.079)                | 12.12                                  |
| DOc1nr   | 6.74                        | 45.47                       | 2.86                                     | 0.088(0.117)                | 13.55                                  |
| DOc2nr   | 6.39                        | 45.45                       | 2.84                                     | 0.080(0.119)                | 13.67                                  |
| DOc3nr   | 4.77                        | 45.70                       | 2.79                                     | 0.088(0.113)                | 13.55                                  |
| DOc4nr   | 5.57                        | 45.57                       | 2.76                                     | 0.095(0.115)                | 13.37                                  |

* Nomenclature: g, pc, and c represent group, poor cluster, and cluster potentials, respectively; 1 indicates no preheating; 3 and 4 represent increasing levels of preheating; and nr indicates no reset.

  a Emission-weighted temperature within $r_{\text{vir}} = 0.88, 1.47$, and $2.63$ Mpc for group, poor cluster, and cluster, respectively.

  b Bolometric X-ray luminosity within $r_{\text{vir}}$.

  c Baryon fraction in hot gas within the total baryon fraction including dropout.

  d Entropy factor at $0.1r_{\text{vir}}$.

  e Baryon fraction in hot gas within $r_{\text{vir}}$; the total baryon fraction including dropout mass is shown in parentheses.

  f Total cooled dropout mass.
Cooled mass profiles for representative DO group and cluster models are shown in Figure 5, and the total dropout mass within the virial radius $M_{\text{cold}}$ is listed in Table 3. It is remarkable that the dropout mass distributions for the groups (DOg1 and DOg4) resemble the de Vaucouleurs profile of NGC 2563 shown with a dotted line in Figure 5. The total dropout mass $M_{\text{cold}}$ is also similar to total stellar masses of galaxy groups. The similarity with a de Vaucouleurs profile is coincidental, since hierarchical merging can also do this and is more plausible physically. Moreover, in a more realistic model the mass dropout profiles would be lowered by internal supernova heating (feedback) not included in the DO models. The dropout profiles in Figure 5 for groups are almost identical for all models within $\log r_{\text{Kpc}} < 0.5$ since this gas cooled before $t_h$ when all the models for given $r_{\text{vir}}$ were identical. In the more important interval $0.5 \lesssim \log r_{\text{Kpc}} \lesssim 2.1$ all dropout profiles exceed that of the profile just before preheating at $t_h$ (dot-dashed line), which for $\text{DOg}(t_h)$ terminates at $\log r_{\text{Kpc}} = 2.1$, the location of the accretion shock at $t_h$. In this range we see that more dropout mass is deposited in models with less preheating (DOg1) or with no uniform reset at $t_h$ (see below). The dropout profiles for cluster flows behave in a qualitatively similar manner but are 30–100 times denser than NGC 2563 in $\log r_{\text{Kpc}} \lesssim 1.2$. The dropout density in this region can be reduced by $\sim 10$ (without much influencing $L$ and $T$) if the initial top-hat perturbation is more extended, less dense, and more massive. Nevertheless, the high-density mass dropout cores in DO cluster models indicate that our mass dropout assumptions are inappropriate, at least on cluster scales. Finally, each of the mass dropout profiles has a small density peak at $\log r_{\text{Kpc}} \sim 0.6$ kpc; this feature is an artifact of mass dropout that accompanied the first compression and heating of baryonic gas in the top-hat perturbation.

DO models are also sensitive to the epoch of preheating. For example, when $t_B$ is increased to 2 Gyr, the final luminosities are reduced by factors of 6, 30, 75, and 140 for models $\text{DOg1} \rightarrow \text{DOg4}$. We have also computed “no-reset” dropout models in which the temperature is increased at $t = 0.5$ Gyr without altering the gas density profiles. In models $\text{DO1nr}$, $\text{DO2nr}$, $\text{DO3nr}$, and $\text{DO4nr}$ the temperature was increased throughout the flow by $0.5 \times 10^7$, $1.0 \times 10^7$, and $3.0 \times 10^7$ K, respectively. Global parameters for $\text{DO}n$ models for groups and clusters are listed in Table 3. The locus of clusters in the $L$-$T$ plot is not strongly influenced by ignoring the reset, but the final group emission-weighted temperatures are increased by about 40% (Table 3). Emission-weighted temperatures reflect the temperature of gas in the high-density cores. If we had used mass-weighted temperatures, the temperatures for $\text{DO}n$ models would have been nearly equal to $\text{DOg}$ temperatures.

In general, preheating is less effective in the no-reset models since the heating is radiated away by the high gas densities after time $t_h$. As a result, the entropy profiles $S(r)$ for these models vary as $S \sim r$ in $r \lesssim 0.1 r_{\text{vir}}$.

3.4. Models with Star Formation and Central Galaxy

In this GA series of gasdynamical models we abandon the hypothesis of universal preheating and assume that all heating results from normal star formation inside the group or cluster. This is similar to the approach we have used to reproduce the X-ray emission profile observed in the giant elliptical NGC 4472 (Brighenti & Mathews 1999a). The dark halos evolve just as in the previous models, but the intergalactic baryonic gas is assumed to remain at $T = 10^4$ K until it arrives at the accretion shock. We assume that stars form at some early time, $t_s \sim 2$ Gyr (redshift $z = 3$), after enough baryons have entered the dark potential. Before time $t_s$ we use the dropout model to approximate the distribution of cooled baryonic mass. At time $t_s$, however, the baryons are rearranged into a density profile similar to that of a luminous elliptical galaxy. We use this same galaxy core at the centers of poor cluster and cluster calculations with an additional extended stellar component approximated with a King distribution; the gravity produced by these extended cluster stars has almost no influence on the gasdynamics. At time $t_s$ we also release the appropriate SN II energy within the shock radius $r_{\text{sh}}$ in proportion to the local gas density. Shortly thereafter, an SN II–driven starburst wind occurs in galaxy group halos, rapidly expelling most of the hot gas from the vicinity of the central group. A strong shock moves upstream against the converging cosmic gas. The gas that participated in the starburst wind reverses velocity and later shocks back onto the group for the second time, with a further entropy increase. For the deeper dark matter halos in poor clusters and clusters, the starburst cannot expel much gas beyond the current virial radius. Within the half-light radius of the central galaxy most of the hot gas is provided by stellar mass loss. For the GA series of models we include addi-

![Fig. 5](image-url)

**Fig. 5.** Density profiles of cooled (dropout) gas at 13 Gyr for groups (upper panel) and clusters (lower panel). **Thick solid lines:** Groups and clusters with no preheating, DOg1 and DOc1. **Thick dashed lines:** Groups and clusters with maximum preheating, DOg4 and DOc4. **Thin solid lines:** Groups and clusters with no preheating and no reset, DOg1nr and DOc1nr. **Thin dashed lines:** Groups and clusters with maximum preheating and no reset, DOg4nr and DOc4nr. **Thin dot-dashed lines:** Groups and clusters at time 0.5 Gyr, just before reset. **Dotted lines:** de Vaucouleurs mass profile for elliptical galaxy NGC 2563.
tional terms in the gasdynamical equations to allow for stellar mass loss and heating by stars and SNe Ia; these modified equations are described in detail in Brighenti & Mathews (1999a).

Our GA models are based on the mass distribution in galaxy group NGC 2563. The central elliptical galaxy has luminosity $L_B = 7.44 \times 10^{10} L_{B,\odot}$ (distance of 78 Mpc) and total stellar mass $M_* = 7.57 \times 10^{11} M_{\odot}$. In addition, Zabludoff & Mulchaey (1998) have identified about 45 galaxies in the group surrounding NGC 2563. Using the approximate morphological types of Zabludoff & Mulchaey (1998) and $M/L_B$ ratios from Fukugita et al. (1998), we estimate that the total stellar mass in the NGC 2563 group is at least 1.5 times that of the central elliptical galaxy. In the models discussed here we assume that the stellar mass of the entire group is twice that of the central galaxy NGC 2563. The contribution of outlying group members to the total stellar mass of groups is highly variable in galaxy groups and is often considerably larger than that for NGC 2563.

Immediately after the time of star formation $t_a$ the ratio of stellar to total baryons within the accretion shock is $M_*/M_b = 0.52$. This ratio is based on the estimated stellar mass of the NGC 2563 group, but we use this same ratio in poor clusters and cluster flows. We note that the fraction of stellar baryons exceeds the cosmic average $Q_b/Q_0 = 0.09$ at zero redshift (Fukugita et al. 1998). However, additional gas accretes into the virial radius after time $t_a$ and by the present time $M_*/M_b$ decreases to 0.27 in the GA2 model and to 0.15 in models GApc2 and GAc2. The final ratio of stellar to gas mass inside $r_{vir}$ is $M_*/M_{gas} = 0.60$ for GA2 and 0.23 for GApc2 and GAc2. In Figure 6 we show the spatial variation of the relative mass in baryons and gas for models GAg1 an GAg4. The relative mass of baryons $f_b = M_b/M_{tot}$ also includes the dropout mass of cooled gas. Note that the gas fraction $f_g = M_{gas}/M_{tot}$ is lower than the cosmic value even at the virial radius and that its value is sensitive to the total amount of SN II energy released.

Except for the ACDM cosmology assumed here, the gasdynamical calculations, stellar mass-loss rates, and SN Ia rates that we use are identical to those described in Brighenti & Mathews (1999a). We assume distributed mass dropout with parameter $q = 1$. The energy provided by SNe II is estimated by assuming that $E_{SN} = 10^{51}$ ergs is released from stars with initial masses greater than 8 $M_{\odot}$ and that $\eta_{II}$ SNe II are produced per solar mass of stars formed. For a typical Salpeter IMF (slope $x = 1.35$, $m_{low} = 0.08$, $m_{high} = 100$) we find $\eta_{II} = \eta_{II,\text{avg}} = 6.81 \times 10^{-3}$. The SN II energy delivered to the hot gas in a galaxy group or cluster of total stellar mass $M_* = M_0 \eta_{II} \epsilon_{SN} E_{SN}$, where $\epsilon_{SN}$ is the efficiency that the supernova energy is delivered to the thermal energy of the hot gas. In cosmological simulations the efficiency of SN II feedback is often chosen to be $\epsilon_{SN} \sim 0.1–0.2$, to allow for radiative losses. Our calculation is somewhat different since we explicitly allow for radiative losses in the thermal energy equation, although we also assume that the supernova blast waves interact directly with the hot gas, not with cold, dense clouds as might be expected in star-forming regions. We therefore consider several values of the composite parameter

$$\eta^* \equiv (\eta_{II}/\epsilon_{SN}) (E_{SN}/10^{51}) \epsilon_{SN},$$

which is expected to be of order unity. For the GA models we consider four values: $\eta^* = 0.5$, 1, 2, and 4, designated as GA1, GA2, GA3, and GA4, respectively. Since $Q_b/Q_0$ is the same in all GA models, the gas temperature following the approximations we have made in the early evolution of groups. The GA2 and GA4 luminosities and temperatures are within about 10% and 25% of the values observed in NGC 2563 (see Table 4 for further details). All GA models also lie near the upper envelope of the Helsdon-Ponman group data, where strong cooling flows are dominated by a massive central elliptical galaxy as we have assumed. In general, as $\eta^*$ increases along the sequence GAg1–GAg4, the X-ray luminosities decrease. However, the nonmonotonic behavior of model GAg3, $L_{GAg1} > L_{GAg3} > L_{GAg2}$, can be understood by competing influences on $L$: larger heating ($\eta^*$) decreases the hot gas density, which lowers $L$, but as $\eta^*$ increases less gas cools and the larger surviving hot gas mass increases $L$.

Values of $\eta^*$ as large as 4 used in model GAg4 may not be unreasonable. Mathews (1989) estimated the stellar mass-to-light ratio $M_*/L_V$ of luminous elliptical galaxies using single-burst stellar populations with power-law IMFs having many slopes and mass limits. He showed that the Salpeter slope $x = 1.35$ is inconsistent with $M_*/L_V \sim 9$, which is typically observed in luminous elliptical galaxies, while shallower IMF slopes, $x \approx 0.7 \pm 0.3$, give satisfactory $M_*/L_V$ for all reasonable upper and lower mass limits. A power-law IMF characterized with slope $x = 0.7$ and mass limits $m_{low} = 0.08$ and $m_{high} = 100$ delivers much more SN II energy than the Salpeter IMF, $\eta_{II}/\eta_{II,\text{avg}} = 3.5$, which may justify our largest values of $\eta^*$.

![Figure 6](image_url)
For the GAg models we have also explored varying the time \( t_a \) when the SN II energy is released and the radial distribution where the SN II energy is deposited. For the standard model, GAg2, we varied \( t_a \) from 2 to 1.5 or 1 Gyr and found that the computed points in the \( L-T \) plane at time \( t_a = 13 \) Gyr were nearly unchanged. In addition, we repeated the GAg2 calculation but applied all of the SN II energy only to (denser) gas within half the accretion shock radius at time \( t_a = 2 \) Gyr. The final luminosity increased slightly since the more central heated gas was denser and lost a larger fraction of its energy and entropy to radiation. We conclude that the positions of the group GAg models in the \( L-T \) plot (Fig. 1d) are not sensitive to the time or spatial dependence of the SN II energy release.

For completeness we have also computed GApc and GAc models for poor clusters and clusters. These results shown in Figure 1d and Table 4 appear to have temperatures about 50% lower than those of the preheated models or the corresponding observations. While our GA assumptions are reasonable for group evolution, they are less appropriate for clusters. For example, we assume that clusters grow from a single-seed galaxy group in the core, ignoring the complex merging events by which groups combine to form large clusters.

**3.4.2. S-T Plot and Entropy Distribution for GA Models**

The group models GAg fall nicely among the observations in the S-T plane shown in Figure 2d regardless of the heating parameter \( \eta^* \). This insensitivity of \( S(r = 0.1 r_{vir}) \), to the initial SN II energy \( \eta^* \) is a result of radiative losses in this inner region. Strong radiative cooling at the galactic center regulates the central density there to \( n_e \sim 0.1 \) cm\(^{-3}\), and the temperature profile adjusts to maintain hydrostatic equilibrium in the common potential of all GA models. Therefore, \( S = T/\eta^*^{2/3} \) evolves to a similar value for all \( \eta^* \). The results for poor clusters and clusters are less satisfactory. Some of the small perturbations of the entropy at \( r = 0.1 r_{vir} \) discussed earlier are also present in the GA models but tend to be smoothed as a result of radiative losses and mass dropout. As before, when the entropy and temperature are mass averaged within \( r_{vir} \), the behavior is much more reasonable, as shown in Figure 4d.

Final entropy profiles \( S(r) \) are shown for GAg and GAc models in Figure 3. The observed entropy profile for NGC 2563 is shown with the GAg models. The agreement is quite good although our models are somewhat denser overall with slightly lower \( S(r) \). As \( \eta^* \) increases, the GAg models have progressively more extended regions of high entropy that project beyond the current virial radius. These entropy features are unlike any of the other models and, if they could be observed, would be a clear signature of the internal heating scenario. The outer GAg flows contain two outward-facing shocks. The outer shock is the starburst blast wave that began at time \( t_a \); the inner shock that occurs close to \( r_{vir} \) is the accretion shock. Variations in SN II heating have little effect on the entropy profile or accretion shock radius in the GAc solutions because of their much greater mass. A positive entropy gradient \( dS/dr > 0 \) extends to very small radii in both GAg and GAc solutions in Figure 3. This is due to mass ejection of low-entropy gas from galactic stars and radiative cooling in high-density gas within the deep central stellar potential.

**4. DISCUSSION AND SUMMARY**

In the previous sections we have described the heating and dynamical evolution of hot gas in galaxy groups and clusters in a flat \( \Omega_{CDM} \) universe with a special emphasis on the gas entropy. The motivation for our interest in this problem can be traced to Kaiser (1986, 1991), who first noted that the X-ray luminosities of groups and clusters vary with gas temperature more steeply than that expected from bremsstrahlung emission in purely adiabatic flow with adiabatic shocks, \( L \propto T^2 \). The observed steeper variation
$L \propto T^3$ or $T^4$ can be understood if cosmic gas is heated by some nongravitational process. The density and X-ray luminosity of hydrostatically supported gas in dark halos are both lower when the gas is heated. If hot gas in both groups and clusters experienced the same level of heating, the luminosity of groups should be disproportionately lower since the heating in the adiabatic accretion shock is much greater in clusters, typically masking the amount of nonadiabatic heating required to account for the steep $L-T$ variation.

If gas and dark matter scale homologously within the virial radius and if all the gas that passes through the accretion shock remains within $r_{\text{vir}}$, the gas density should be the same at any fraction of $r_{\text{vir}}$, regardless of the mass of the cluster. In this case the entropy factor $S = T/n_e^{2/3}$ is proportional to $T$. Lloyd-Davies et al. (2000) have used the X-ray data to estimate the entropy factor $S_{0.1} = T/n_e^{2/3}$ at 0.1$r_{\text{vir}}$ in group and cluster gas. They find that when the $S_{0.1} \propto T$ relation is normalized to massive clusters, the values of $S_{0.1}$ for groups are too large to fit the same relation. Either some gas in groups flowed out because it was internally heated, or an insufficient amount of gas entered the group at early times because the gas was preheated before the accretion occurred.

This leads directly to the question we have addressed here: was the diffuse gas in galaxy groups and clusters preheated by some external process at high redshifts, or was the heating internal, as a result of supernovae that accompanied normal star formation? Some recent studies of this question have invoked a universal cosmic preheating from sources unrelated to star formation. In view of its importance for galaxy formation, we have developed an ensemble of gasdynamical models with and without preheating.

### 4.1. External Preheating

To investigate the consequences of universal preheating, we study the accumulation of gas in group and cluster dark halos with three progressively more realistic assumptions: AD flows with adiabatic shocks, CO flows with radiative cooling (Tozzi & Norman 2001), and finally DO flows with mass dropout and radiative cooling (Knight & Ponman 1997; Nulsen & Fabian 1995, 1997). In order to compare our results with those of previous studies, we also assume that the gas temperature and density are reset to uniform values at the moment when the preheating occurred, i.e., excess gas inside the dark halo is removed. For most of our models the reset is assumed to occur at time $t_\text{r} = 0.5$ Gyr or redshift $z_\text{r} = 9$. In spite of its popularity in the current literature, there is some uncertainty about the reset and preheating procedure. While very few stars have formed at these high redshifts and the only collapsed objects correspond to very small stellar systems, the top-hat perturbations that we use to generate present-day group and cluster halos have collected baryonic gas that is removed at time $t_\text{r}$ by the reset assumption. We have also done many calculations with no reset. The dark halos evolve in a normal way, initiated by a top-hat perturbation and cooling toward an NFW profile in a flat $\Lambda$CDM universe. The final halo is insensitive to the top-hat perturbation, i.e., the same halo can be produced by a variety of different top-hat density amplitudes with appropriately chosen top-hat radii.

In general, we find that data in the $L-T$ plot (Fig. 1) can be fitted with AD, CO, or DO flows with reset provided the preheating is sufficiently intense, 1.3–3.9 keV per particle ($K_{34} = 0.25$–0.76). However, these strongly preheated flows typically have entropies $S_{0.1}$ for groups and poor clusters that exceed observed values (Fig. 2). Values of the entropy and temperature that are mass weighted within the virial radius obey the $S \propto T$ similarity relation except for the most strongly preheated group gas (Fig. 4), but these cannot be compared with current observations. However, a variety of computational and physical problems have appeared in our models with cosmic preheating. For example, weakly heated AD models not only are less successful in the $L-T$ plot but also show irregularities due to transient shocks following the reset that persist as irregularities in the entropy profiles $S(r)$ in the final AD1 models (Fig. 3). $S_{0.1}$ may be increased by these spurious shocks. With more computational effort these irregularities could probably be removed. However, it is clear that AD models cannot be correct in spite of their considerable success in fitting the $L-T$ data (with large preheating) and the entropy profiles (with little preheating): adiabatic flows cannot form stars, nor can they radiate X-rays.

When radiative losses are included, as in the CO flows, we find that some preheated models agree with data in the $L-T$ plot and have entropy profiles very similar to those of Tozzi & Norman (2001), who make similar assumptions. However, group models with less preheating and all cluster models except COc4 have enormously massive and luminous X-ray singularities produced by emission from uncooled gas flowing into the center of the cluster. Because of their luminous cores, these models have absurdly high X-ray luminosities and do not correspond to any object observed. Another somewhat technical, but physically real, aspect of CO flows is their tendency to produce nonlinear Rayleigh-Taylor unstable waves that propagate into the core of the flow sometimes at high velocity. The drip waves are Rayleigh-Taylor unstable so they cannot remain perfectly coherent, unlike their representations in our one-dimensional models, and they will tend to be limited by mass dropout, not included in the CO models. Finally, our results differ from those of Tozzi & Norman (2001) in that the accretion shock is very close to the virial radius for all levels of preheating considered.

To avoid these difficulties encountered in the CO models, we performed a final DO series of preheated models in which gas is allowed to cool to very low temperatures everywhere within the virial radius. This is a standard assumption used in models of cooling flows. As before, strongly preheated DO models that fit the $L-T$ data have entropies $S_{0.1}$ that exceed observed values. While the ultraluminous X-ray cores of the CO flows are no longer present in the DO models, the accumulated mass of cooled (dropout) mass can be large, particularly in massive clusters where it exceeds the central mass densities of luminous elliptical galaxies by 10–100.

We have also performed calculations of all types of externally preheated flows with no uniform reset of the gas density and temperature at time $t_\text{r}$. In these models the cosmic gas temperature is heated by various amounts throughout the flow at $t_\text{r}$, but the density profile is not altered. To reduce the final luminosity $L$ by the same amount as in the reset models, the no-reset models require much higher levels of preheating to compensate for the energy radiated away from denser cores. The COnr models are totally unacceptable because of the intense concentration of X-ray emission from the core where all the gas has
cooled. DOgnr models are more similar to their DO counterparts since most of the heating is radiated away by dense gas in the core. Although DOgnr flows are somewhat hotter than the corresponding DOg flows, they nevertheless have lower central entropies $S_{0.1}$.

For a variety of reasons, none of our preheated models are particularly attractive, with or without reset. In addition to gasdynamical concerns, the agency that heats the gas is unclear. Since the cosmic gas density is higher in the early universe, more energy is required to reach the same adiabat than at lower redshifts. In the flat $\Lambda$CDM universe global preheating by SNe II during star formation is unable to heat all the gas sufficiently at redshifts $z \gtrsim 1$ to achieve agreement with galaxy group observations in the $L$-$T$ plane. There may be enough energy in AGNs to heat the gas at high redshifts, but it is unclear if this energy can be widely distributed in the intergalactic gas and not just concentrated near the AGNs.

In comparing preheated models with observations, we place more emphasis on the $L$-$T$ plane than on the $S_{0.1}$-$T$ plane. The $S_{0.1}$ data are of lower quality because they typically refer to the outermost detectable X-ray emission from groups where the background corrections may be troublesome. In addition, the virial radius must be estimated to derive $S_{0.1}$ from the observations. Some of our models are also less certain in the inner parts of the flow $r \lesssim 0.1r_{\text{vir}}$ where the entropy can be increased by early shock waves or rapidly moving dip waves.

4.2. Internal Heating by Supernovae

In our final series of GA models the external preheating assumption is replaced with internal heating by SNe II associated with star formation at time $t_*=2$ Gyr and redshift $z_*=3$ (see also Loewenstein 2000; Bryan 2000). This internal heating is distributed within the accretion shock ($\sim r_{\text{vir}}$) in proportion to the local gas density. Immediately following $t_*$ a strong starburst wind occurs in the GA group solutions. High-entropy gas produced by the starburst shock currently extends beyond the virial radius. Accompanying the SN II energy release is the formation of a luminous elliptical galaxy at the center of the group or cluster flow. As a guide, we have chosen the stellar mass of the NGC 2563 group to calibrate the amount of SN II energy delivered to the hot gas in groups. This same SN II heating per unit baryonic mass is applied to GA models for clusters. We have explored the effect of varying the time $t_*$ of star formation and altering the distribution of the SN II energy within $r_{\text{vir}}$, but the final results are surprisingly insensitive to these parameters. The GA models resemble DO models without reset since both include cooling mass dropout and have dense baryonic cores; the main difference is that the GA models are heated internally and DO models are heated universally.

While we have not attempted to produce a detailed model for the NGC 2563 group, we find that the X-ray luminosity and temperature observed in NGC 2563 are almost exactly matched by our GA group model at time $t_*=13$ Gyr when heated with SN II energy expected from a Salpeter IMF. The data in the $S_{0.1}$-$T$ plane are also nicely fitted by the group GA models. Finally, we find that our standard GA group models agree well with the entropy distribution $S(r)$ observed in NGC 2563. Excellent agreement with observations in both the $L$-$T$ and $S$-$T$ plots can be achieved with a range of 8 in the SN II energy released per unit stellar mass, corresponding to different IMFs. However, for the best results we require that at least $\sim 0.2$ of the energy released by SN II from early star formation directly heats the hot gas. The local environment of the early SN II explosions may differ from star-forming regions in our Galaxy in that the supernova blast waves propagate into the hot gas, not into cold, dense clouds that may radiate away much of the supernova energy. Of course, the hot gas heating efficiency could be less than 0.2 if the IMF were more top heavy than expected. We also present GA models for clusters, although our physical model of monolithic growth (without detailed hierarchical merging) is less appropriate for cluster masses.

Mushotzky & Scharf (1997) have shown that the evolution of data in the $L$-$T$ plane is very weak out to redshifts $z \sim 0.4$. Our GA group models also exhibit this same slow evolution. For example, the mean bolometric X-ray luminosity and gas temperature for the four GA models we consider differ at $z=1$ by only 45% and $-7\%$, respectively, from the same averages at zero redshift, indicating that the temperature is stable and that the luminosity may be declining slightly.

In view of the generally good agreement with observations, we conclude that galaxy group models with internal SN II heating fit the data better and more plausibly than any of the externally preheated models we have considered. The production of SN II energy and the transfer of this energy to the hot gas may be a concern for the internal heating models we prefer, but there has been no satisfactory explanation of the sources of the much greater energy associated with universal, external preheating at high redshifts.

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