2003

How do galaxies get their gas?

N Katz
University of Massachusetts - Amherst, nsk@astro.umass.edu

D Keres

R Dave

DH Weinberg

HOW DO GALAXIES GET THEIR GAS?

Neal Katz, Dusan Keres
University of Massachusetts, Department of Astronomy, Amherst, MA 01003

Romeel Davé
University of Arizona, Steward Observatory, Tucson, AZ 85721

David H. Weinberg
Ohio State University, Department of Astronomy, Columbus, OH 43210

Abstract Not the way one might have thought. In hydrodynamic simulations of galaxy formation, some gas follows the traditionally envisioned route, shock heating to the halo virial temperature before cooling to the much lower temperature of the neutral ISM. But most gas enters galaxies without ever heating close to the virial temperature, gaining thermal energy from weak shocks and adiabatic compression, and radiating it just as quickly. This "cold mode" accretion is channeled along filaments, while the conventional, "hot mode" accretion is quasi-spherical. Cold mode accretion dominates high redshift growth by a substantial factor, while at $z < 1$ the overall accretion rate declines and hot mode accretion has greater relative importance. The decline of the cosmic star formation rate at low z is driven largely by geometry, as the typical cross section of filaments begins to exceed that of the galaxies at their intersections.

The conventional sketch of galaxy formation has its roots in classic papers of the late '70s and early '80s, with the initial discussions of collapse and cooling criteria by Binney (1977), Rees & Ostriker (1977), and Silk (1977), the addition of dark matter halos by White & Rees (1978), and the disk formation model of Fall & Efstathiou (1980). According to this sketch, gas falling into a dark matter potential well is shock heated to approximately the halo virial temperature, $T_{\rm vir} = 10^6 (v_{\rm circ}/167\,{\rm km\,s^{-1}})^2\,{\rm K}$. Gas in the dense, inner regions of this shock heated halo radiates its thermal energy, settles into a centrifugally supported disk, and forms stars. Mergers of disks can scatter stars onto disordered orbits, producing spheroidal systems, which may regrow disks if they experience subsequent gas accretion. Over the last decade, the ideas of these seminal papers have been updated and extended into a powerful "semi-analytic" framework for galaxy formation calculations (e.g., White & Frenk 1991; Kauffmann et al. 1993; Cole et al. 1994; Avila-Reese et al. 1998; Mo, Mao, & White 1998; Somerville & Primack 1999).

The geometry seen in N-body and hydrodynamic cosmological simulations, where the densest structures often form at the nodes of a filamentary network, is clearly more complicated than the spherical geometry envisioned in semi-analytic models. Nonetheless, a substantial fraction of the gas in these simulations does shock heat to $T \sim T_{\rm vir}$, and some of this gas does cool and settle into galaxies. The approximate agreement between semi-analytic and smoothed particle hydrodynamics (SPH) calculations of galaxy masses (e.g., Benson et al. 2001; Yoshida et al. 2002) has therefore been taken as evidence that the conventional sketch, while idealized, captures most of the essential physics.

There is, however, a long history of results suggesting that this outline of the way that gas gets into galaxies is at best half of the story, and perhaps the less important half. Binney (1977) argued that the amount of shock heating could be small for plausible physical conditions, with only a fraction of the gas reaching temperatures $\sim T_{\rm vir}$. In the first SPH simulations of forming galaxies (Katz & Gunn 1991), which had idealized initial conditions but included small scale power leading to hierarchical formation, most of the gas never heated above $T \sim 3\times10^4\,$K, with much of the cooling radiation therefore emerging in the Lyα line. Katz & White (1993) showed the importance of filamentary structures as channels for gas accretion in simulations with cold dark matter (CDM) initial conditions.

Two recent studies, based on SPH simulations of cosmological volumes, reveal the situation even more starkly. First, Fardal et al. (2001) show that most of the cooling radiation in their simulations comes from gas with $T < 2\times10^4\,$K, again implying that a significant fraction emerges in the Lyα line. Since gas starting at $T \sim 10^6\,$K *must* radiate 90% of its thermal energy by the time it cools to $T \sim 10^5\,$K, Fardal et al. (2001) argue that the majority of the gas entering galaxies (indeed, the majority of the gas experiencing any significant cooling) must not be heated to the virial temperature of any dark matter halo resolved by the simulation. Second, Kay et al. (2000) directly track temperature histories of particles that end up in their simulated galaxies, and they report that only 11% of these particles were ever heated above $10^5\,$K.

We have begun to examine this issue more closely, using an SPH simulation of a $22.222h^{-1}\,$Mpc box with an LCDM cosmology ($\Omega_m = 0.4$, $\Omega_\Lambda = 0.6$, $n = 0.95$, $h = 0.65$, $\sigma_8 = 0.8$) and 2×128^3 particles.

The physical assumptions and numerical techniques are described by Katz et al. (1996) and Davé et al. (1997). The resolution limit for galaxies, a baryon mass corresponding to $64m_{\rm SPH}$, is $6.7 \times 10^9 M_\odot$ or a circular velocity of $v_{\rm vir}^{\rm min} = 46(1+z)^{1/2}\,{\rm km\,s^{-1}}$. Figure 1 shows our key result. At four representative redshifts, we trace back each particle that was recently added to a galaxy and record the maximum temperature $T_{\rm max}$ that it had at any previous output. Solid histograms show the distributions at each redshift in physical units, demonstrating the decline of the overall accretion rate at low redshifts, while the dotted histograms are renormalized to better show the relative distribution.

Our star formation and galaxy identification algorithms require that gas particles cool to $T < 3\times10^4$ K and reach an overdensity of $\rho/\bar{\rho} > 10^3$ before they are eligible to form stars or be counted towards a galaxy's

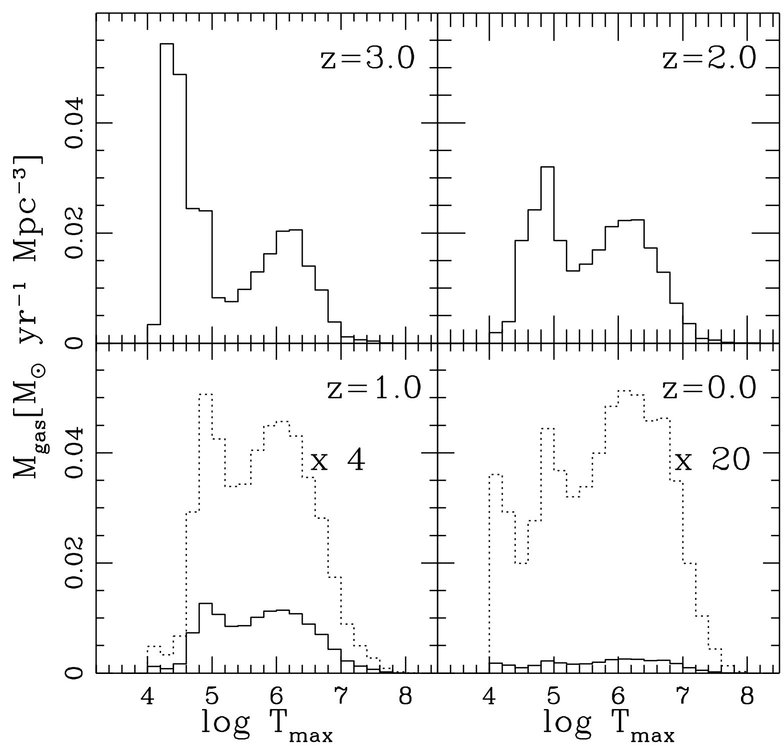

Figure 1 The maximum temperature reached by gas accreted into galaxies at the specified redshift. The dotted line rescales the histogram to better show the relative amount at different temperatures. Note the two distinct modes of gas accretion, the "cold mode" and the "hot mode".

baryon mass component. Figure 1 shows that gas reaches these physical conditions via two distinct routes. One of these corresponds to the conventional "hot mode" of gas accretion outlined above, with gas heating to $T \geq T_{\rm vir} \sim 10^5 - 10^7$ K before cooling. In the second, "cold mode" of accretion, the maximum gas temperature is $T_{\rm max} < T_{\rm vir}$. The cold mode dominates the total amount of accretion by a large factor at high redshift, and the hot mode becomes progressively more important at low redshift. The characteristic $T_{\rm max}$ of the cold mode rises with time, and the range of temperatures in each mode becomes broader, so that they merge into a fairly continuous range of $T_{\rm max}$ values by $z = 0$. Overall, 42% of the mass in galaxies at $z = 0$ has $T_{\rm max} < T_{\rm vir}^{\rm min}$ when it was accreted, which is a firm lower limit to the amount of "cold mode" accretion since most galaxy halos have $T_{\rm vir} > T_{\rm vir}^{\rm min}$. Since our simulation outputs are spaced by $\Delta t \sim 0.3$ Gyr we always underestimate a particle's true value of $T_{\rm max}$. However, the cooling times are typically longer than Δt, and the concordance of Figure 1 with the findings of Fardal et al. (2001), whose cooling radiation argument applies to individual simulation outputs, and of Kay et al. (2000), who examined every timestep in their simulation, implies that this finite time resolution does not qualitatively change our results.

What is going on? One possibility, that the gas is cooling in halos with low $T_{\rm vir}$, can be immediately dismissed, since the lowest mass halos resolved by the simulation have $T_{\rm vir} \sim 76,000(1 + z)$ K. Furthermore, we have shown elsewhere (Murali et al. 2002) that galaxies in these simulations gain most of their mass by smooth accretion, not by mergers with pre-existing systems. Even the more massive (and thus better resolved) galaxies in our simulations are gaining most of their mass by accreting gas that has never been hot.

A second possibility is that this result is a numerical artifact: gas that should be shock heated to high temperature is not. We find qualitatively similar results at $z = 3$ in a simulation whose mass resolution is a factor of eight higher than the one illustrated in Fig. 1, and at $z = 0$ in a simulation whose mass resolution is a factor of eight lower. Thus, the basic result illustrated here is not sensitive to resolution over the range that we have been able to test. Cold accretion is also evident in much higher resolution SPH simulations of the formation of individual galaxies (Katz & Gunn 1991; Navarro & Steinmetz, priv. comm.) and in the Virgo Consortium's simulations of cosmological volumes (Kay et al. 2000), implying that any artifact would have to be generic to SPH, not merely to our specific implementation of it. However, confirmation by an independent numerical method with better shock capturing properties is clearly desirable. Cen & Ostriker (1999, fig. 4) find a broad temperature distribution for cooling radiation in their Eulerian hydro simulation, suggesting that much of the gas in this simulation also cools without ever reaching $T \geq 10^6\,$K. Kravtsov (priv. comm.) reports preliminary findings similar to ours in simulations that use an adaptive refinement grid code with a shock capturing hydrodynamics algorithm. Present evidence, therefore, suggests that the bimodal $T_{\rm max}$ distribution is a genuine physical result, at least given the physical assumptions of these simulations.

Our preliminary investigations suggest that these two accretion modes are geometrically distinct, in addition to being thermally distinct. Particles accreted in the hot mode come from a quasi-spherical distribution, as envisioned in the conventional galaxy formation scenario. Particles accreted in the cold mode, by contrast, travel to galaxies along filamentary "highways." Our tentative picture, therefore, is that the first gas to enter filaments is only mildly shock heated; as it moves along the filaments towards their nodes of intersection, it is heated by adiabatic compression or by further mild shocks, but the relatively slow heating and short cooling times allow the gas to radiate its energy as quickly as it is gained. Nagai & Kravtsov (2002) show, in a simulation with no radiative cooling, that the core of a filament can indeed have much lower entropy than the outer regions. Gas must dissipate a large amount of gravitational potential energy before it can join an object as dense as a galaxy, but filamentary accretion allows it to do so without ever reaching a high temperature.

The existence of an efficient, low temperature, filamentary accretion mode could have important implications for the origin of galaxy angular momenta and for the rapid decline of the cosmic star formation rate (SFR) at $z < 1$ (Madau et al. 1996). If a galaxy accretes much of its baryonic mass along filamentary structures, then the specific angular momentum distribution of its gas and stars may have little direct connection to that of its parent dark matter halo, even if the total specific angular momenta are of the same order. In the traditional picture of gas accretion, the decline of the cosmic SFR is attributed mainly to longer cooling times in the hotter, lower density halos that form at lower redshift. However, it is not clear that this effect is strong enough in itself to produce the observed sharp drop in the cosmic SFR from $z = 1$ to $z = 0$ (e.g., Baugh et al. 1998; Somerville & Primack 1999; the observations themselves have significant uncertainties). We have shown in Murali et al. (2002) that the cosmic star formation rate closely tracks the smooth gas accretion rate and not the rate by which galaxies gain gas through merging. If filamentary accretion dominates over quasi-spherical accretion, then the decline of the cosmic SFR may be driven largely by geometrical effects. At high redshift, the sizes of filaments are well matched to those of galaxies, and they can act as efficient umbilical cords, channeling gas to the embryonic systems at their intersections. At low redshift, however, the cross sections of typical filaments grow to hundreds of kpc, so they tend to deliver their gas to groups and clusters (where it is heated in accretion shocks) rather than directing it to individual galaxies.

Our simulations incorporate supernova feedback, but its impact is usually mild because the energy is deposited in a dense medium with a short cooling time. The stellar masses of the simulated galaxies appear to be systematically too high relative to estimates from the observed luminosity function, a problem that is fairly generic to hydrodynamic simulations with similar physical assumptions (e.g., Katz et al. 1992; Pearce et al. 1999; Nagamine et al. 2001). Until the origin of this discrepancy is better understood, it is difficult to assess the importance of cold mode gas accretion in the real universe, even if it is clearly important in the simulations themselves. Shaun Cole (priv. comm.) has pointed out that a "cold mode" of gas accretion would also appear in a semi-analytic model of galaxy formation if cooling were allowed to proceed unchecked in halos with low virial temperatures, since larger galaxies could then build up by mergers of these small systems, with much of their gas never being heated to high temperatures. However, most semi-analytic calculations suppress this "cold mode" by supernova feedback, which is assumed to be more effective in low mass halos (Dekel & Silk 1986). The current numerical results suggest that cold accretion is smooth and filamentary, in which case efficient star formation and feedback is unlikely to suppress it. Indeed, it is possible that feedback from supernovae or AGN activity is actually more effective in suppressing "hot mode" accretion, where the incoming gas typically has larger geometrical cross section, lower density, and higher entropy. If this is the case, then the relative importance of the cold mode could be even greater than it appears in these simulations.

Clearly there is more to be understood about the physical mechanisms of cold mode gas accretion in numerical simulations, and about its robustness to changes in numerical resolution and hydrodynamics algorithm. However, there is now a substantial amount of evidence, from our own simulations and from others, that cold, filamentary accretion makes an important contribution to the buildup of galaxies. Further investigations of this process could lead to significant revisions in our understanding of galaxy formation and evolution.

References

Avila-Reese, V., Firmani, C., & Hernandez, X. 1998 ApJ, 505, 37

Baugh, C. M., Cole, S., Frenk, C. S., & Lacey, C. G. 1998, ApJ, 498, 504

Benson, A.J., Pearce, F.R., Frenk, C. S., Baugh, C. M. & Jenkins, A 2001, MNRAS, 320, 261

Binney, J. 1977, MNRAS 181, 735.

Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1

Cole, S., Aragon-Salamanca, A., Frenk, C. S., Navarro, J. F., & Zepf, S. E. 1994, MNRAS, 271, 781

Davé, R., Dubinski, J., & Hernquist, L. 1997, New Astron, 2, 227

Dekel, A., & Silk, J. 1986, ApJ, 303, 39

Fall, S. M. and Efstathiou, G. 1980,MNRAS, 193, 189.

Fardal, M. A., Katz, N., Gardner, J. P., Hernquist, L., Weinberg, D. H. & Davé, R. 2001, ApJ, 562, 605

Katz, N., & Gunn, J. E. 1991, ApJ, 377, 365

Katz, N., Hernquist, L., & Weinberg, D. H. 1992, ApJ, 399, L109

Katz, N., Quinn, T., Bertschinger, E., & Gelb, J. M. 1994, MNRAS, 270, L71

Katz, N., Weinberg D.H., & Hernquist, L. 1996, ApJ Supp., 105, 19

Katz, N., & White, S. D. M. 1993, ApJ, 412, 455

Kauffmann, G., White, S. D. M., & Guideroni, B. 1993, MNRAS, 264, 201

Kay, S. T., Pearce, F. R., Jenkins, A., Frenk, C. S., White, S. D. M., Thomas, P. A., & Couchman, H. M. P. 2000, MNRAS, 316, 374

Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388

Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319

Murali, C., Katz, N., Hernquist, L., Weinberg, D. H., & Davé, R. 2002, ApJ, 571, 1

Nagai, D. & Kravtsov, A. V. 2002, ApJ, submitted, astro-ph/0206469

Nagamine, K., Fukugita, M., Cen, R., & Ostriker, J. P. 2001, MNRAS, 327, 10

Pearce, F. R., Jenkins, A., Frenk, C. S., Colberg, J. M., White, S. D. M., Thomas, P. A., Couchman, H. M. P., Peacock, J. A., & Efstathiou, G. 1999, ApJ, 521, L99

Rees, M.J., and Ostriker, J.P. 1977 MNRAS, 179, 541.

Silk, J.I. 1977 ApJ, 211, 638.

Somerville, R. S., & Primack, J. R. 1999, MNRAS, 310, 1087

White, S. D. M., & Frenk, C. S. 1991, ApJ, 379, 52

White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341

Yoshida, N., Stoehr, F., Springel, V. & White, S.D.M. 2002, MNRAS, 335, 762.