THE DENSITY PROFILES OF HOT GALACTIC HALO GAS

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Abstract

Extended gas halos around galaxies are a ubiquitous prediction of galaxy formation scenarios. However, the density profiles of this hot halo gas is virtually unknown, although various profiles have been suggested on theoretical grounds. In order to quantitatively address the gas profile, we compare galaxies from direct cosmological simulations with analytical solutions of the underlying gas equations. We find remarkable agreement between simulations and theoretical predictions. We present an expression for this gas profile with a nontrivial dependence on the total mass profile. This expression is useful when setting up equilibrium galaxy models for numerical experiments.

Subject headings: galaxies: structure — methods: analytical — methods: N-body simulations

Online material: color figures

1. INTRODUCTION

Standard galaxy formation scenarios predict that galaxies have an extended halo of hot gas. This hot gas is gravitationally trapped by the dark matter (DM) potential and cools slowly due to thermal emission (White & Frenk 1991).

These halos of hot gas have been observed around massive elliptical galaxies through their X-ray emission (e.g., Matsushita 2001) and recently around normal quiescent spiral galaxies (Pedersen et al. 2006). These observations provide strong support for the standard galaxy formation scenario.

One missing aspect is the qualitative understanding of the density profile of these hot halos. We therefore investigate the density profiles extracted from virialized galaxies in cosmological simulations as well as theoretical predictions based on the fundamental gas equations. We find remarkable agreement between simulations and theory. We present an analytical expression for the gas profile, which depends nontrivially on the total mass distribution of both baryons and DM.

2. THEORETICAL PREDICTIONS

Galaxies are dynamically old and should therefore have reached a quasi-static equilibrium state. In this state, there is very little radial bulk motion of the hot halo gas, possibly except for the very central region where cooling is important.

Since the gas has frequent collisions, we must treat it through the Navier-Stokes (N-S) equations. The N-S equations apply to any collisional gas or fluid and are three hydrodynamical equations for the velocity vector. The galaxies have reached a quasi-static equilibrium state, and so the N-S equations simplify considerably since all the time-dependent terms disappear.

One of the N-S equations is related to the radial velocity component, and if the rotation of the gas is negligible then it reduces to the normal equation for hydrostatic equilibrium. From this equation, it is straightforward to show that when the mass is dominated by a spherical distribution of matter, then the spherical gas density profile is given as a function of the underlying total matter distribution. One finds that everywhere throughout the galaxy the logarithmic derivative of the gas density,

\[ \beta_g = \frac{\partial \log \rho_g}{\partial \log r}, \]

is given as a function of the logarithmic derivative of the total density, \( \beta_{\text{tot}} \), and the polytropic index, \( \gamma \), which is related to the derivative of the temperature through

\[ \gamma = 1 + \frac{\partial \log T}{\partial \log \rho}. \]

One finds the connection

\[ \beta_g = \kappa(\beta_{\text{tot}} + 2), \]

where the prefactor is defined as \( \kappa = 1/(\gamma - 1) \). In general, \( \gamma \) can be in the range \( 1 \leq \gamma \leq 5/3 \), and when \( \gamma = 1.5 \) we have the connection \( \beta_g = 2(\beta_{\text{tot}} + 2) \). It is interesting to note that even though, in general, the solution in the inner region might differ from the solution in the outer region, as in the hydraulic jump (Watanabe et al. 2003; Hansen et al. 1997), the connection in equation (3) is the same everywhere (Hansen 2003).

If the mass in a given radial range is dominated by the gas itself, which may happen in the very inner region, then the solution is clearly \( \beta_g = -2(-4 \text{ or } -6) \) if the polytropic index is \( \gamma = 1 \text{ (3/2 or 5/3)} \).

We emphasize that the result in equation (3) is based on the simplifying assumption that both the gas density profile and the total mass profiles are power laws, and therefore equation (3) should only be seen as an approximation.

Various other possible behaviors for the gas profile have been proposed besides the one in equation (3), e.g., that the gas density profile could follow that of the DM (Frenk et al. 1999),

\[ \beta_g = \beta_{\text{tot}}. \]

These simulations were considering cluster scales, where cool-

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3 One can show that there are only two asymptotic solutions to the N-S equations for the gas, one being a spherical distribution and one being a disk distribution (Hansen & Stadel 2003).
ing is less relevant (see, e.g., Romeo et al. 2006). Nevertheless, artificially created galaxies used in a range of N-body simulations, e.g., to investigate aspects of gas-cooling in a controlled manner (Kaufmann et al. 2006), are routinely constructed under the assumption in equation (4). These systems are often created through the use of the hydrostatic equilibrium and are therefore stable before cooling is turned on (Kaufmann et al. 2006). The main point of such controlled experiments is, however, to perform detailed investigations of cooling or collisions, and the fact that the density profile is not fully realistic implies that the purpose of these controlled investigations may be lost.

We emphasize that it is important to set up realistic systems when studying cooling, because the cooling rate at high temperatures goes like \( \rho^2 \). If one initiates with an incorrect gas density profile, then the resulting cooling rate will be unrealistic. If one uses a Navarro-Frenk-White (NFW) profile for the gas, then the gas density is overestimated by a factor of about 3 near the disk (Mastropietro et al. 2005), which implies a cooling rate that is an order of magnitude too high. For merging simulations, on the other hand, the overdensity of gas near the central region (if initiated with an NFW profile) turns out to be of little importance (Mastropietro et al. 2005).

Another suggested behavior of the gas density is that it should be virtually independent of the local DM slope, and, e.g., follow a \( \beta \)-profile (Sarazin 1986), where \( \beta_{gas} \) goes from zero in the center to \(-3\beta\) in the outer region, which for the normal assumptions implies \( \beta_{gas} \approx -2 \) in the outer region. It has been noticed both in observations and simulations that the gas in galaxy clusters has a tendency to show larger values of \( \beta \) in the outer region (Navarro et al. 1995; Evrard 1990), which corresponds to the outer gas density slope being steeper than \(-2\) in the outer region. As we show below, this is in agreement with our findings for galaxies.

3. THE CODE AND SIMULATIONS

The code used for the simulations is a significantly improved version of the TreeSPH code, which has been used previously for galaxy formation simulations (Sommer-Larsen et al. 2003). The main improvements over the previous version are as follows: (1) The “conservative” entropy equation solving scheme suggested by Springel & Hernquist (2002) has been adopted. (2) Noninstantaneous gas recycling and chemical evolution, tracing 10 elements (H, He, C, N, O, Mg, Si, S, Ca, and Fe), has been incorporated in the code following Lia et al. (2002a, 2002b); the algorithm includes Type II supernovae (SNe II) and SNe Ia, and mass loss from stars of all masses. (3) Atomic radiative cooling depending both on the metal abundance of the gas and on the metagalactic UV field, modeled after Haardt & Madau (1996), is invoked, as well as a simplified treatment of radiative transfer, switching off the UV field where the gas becomes optically thick to Lyman limit photons on scales of \( \sim 1 \) kpc.

The formation and evolution of a total of 15 individual galaxies, known from previous work to become disk galaxies at \( z = 0 \), was simulated with the above, significantly improved, TreeSPH code. At least two different numerical resolutions were used to simulate each galaxy. Moreover, many of the galaxies were also simulated with different physical prescriptions for the early \( (z \gtrsim 4) \) starbursts (and related SN II–driven energy feedback) found previously to be required, in order to produce realistic disk galaxies. The galaxies were selected to represent “field” galaxies (Sommer-Larsen et al. 2003) and span a range of characteristic circular speeds of \( V_c \sim 100–330 \) km s\(^{-1}\) and virial masses of \( 6 \times 10^{10}–3 \times 10^{12} M_{\odot} \).

The galaxies (galaxy DM halos) were selected from a cosmological, DM-only simulation of box length \( 10 h^{-1} \) Mpc (comoving) and starting redshift \( z = 39 \). The adopted cosmology was the flat \( \Lambda \)CDM model, with \((\Omega_m, \Omega_{\Lambda}) = (0.3, 0.7)\).

Mass and force resolution were increased in Lagrangian regions enclosing the galaxies, and in these regions all DM particles were split into a DM particle and a gas (smoothed particle hydrodynamics [SPH]) particle according to an adopted universal baryon fraction of \( f_b = 0.15 \), in line with recent estimates.

In this Letter, only results of two high-resolution simulations of two large disk galaxies are presented (see Sommer-Larsen 2006 for details). Each simulation contains about \( 3 \times 10^5 \) SPH+DM particles, and for the two simulations, \( m_{gas} = m_\star = 7.3 \times 10^7 \) and \( m_{DM} = 4.2 \times 10^6 h^{-1} M_{\odot} \), and \( \epsilon_{gas} = \epsilon_{\star} = 380 \) and \( \epsilon_{DM} = 680 h^{-1} \) pc \((h = 0.65)\). The gravity softening lengths were fixed in physical coordinates from \( z = 6 \) to \( z = 0 \) and in comoving coordinates at earlier times. A Kroupa initial mass function was used in the simulations, and early rapid and self-propagating star formation (sometimes dubbed “positive feedback”) was invoked (Sommer-Larsen et al. 2003).

The two galaxies have masses similar to those of M31 and the Milky Way, with characteristic circular velocities of \( V_c \approx 245 \) and \( 233 \) km s\(^{-1}\), respectively. At \( z \sim 0 \), each galaxy contains approximately \( 10^5 \) DM and \( 10^7 \) gas and star particles within the virial radius.

At any time, there are satellites at various radii in these galaxies, which produce bumps in the total density profile. In order to reduce these bumps, we have co-added five frames with 1 Gyr spacing, corresponding to the period \( z = 0.3 \) to \( z = 0 \). No major merging was taking place during this period.

4. COMPARING THEORY AND SIMULATIONS

In Figures 1 and 2, we plot the logarithmic derivative of the gas density as a solid line (with open circles) from the simulations. We emphasize that many more details are visible since we consider the derivative of the density profile. In the very central region, the hot gas density profile becomes steep, because the density is calculated including hot gas particles very near the cold, high-density gas disk (i.e., a numerical effect). If these near-disk hot gas particles are excluded, the density slope of the hot gas goes toward zero near the center. Outside \( \log r = 1.4 \), the gas slope falls slowly from \(-1\) in the central region to \(-3\) in the outer region near \( \log r = 2.4 \). The virial radius is approximately \( 250 \) kpc, corresponding to \( \log r = 2.4 \). Farther out, for galaxy K15, the presence of a neighboring galaxy causes the total and hot gas density profiles to flatten.

Let us now compare this behavior of the density profile to the theoretical predictions. The simulated behavior of the gas profile is clearly very different from a \( \beta \)-profile, which should go from zero in the central region to roughly \(-2\) farther out. It therefore appears that the hot gas in dynamically old structures, like a galaxy, is not well described by a \( \beta \)-profile.

We also plot the total density as a dotted line (with open triangles). According to the Santa Barbara comparison (Frenk et al. 1999), the solid line and the dotted line could be similar. It is clear that the behavior of derivatives of the total and gas density are very different everywhere within the virial radius, since the gas does not follow \( \beta_{gas} = \beta_{star} \), although this is often
considered as a realistic initial condition for galaxy models. Our results indicate that such initial conditions are not in agreement with results for galaxies formed in ΛCDM cosmological simulations.

As the dashed line (with filled circles), we have the prediction from equation (3). There is impressive agreement for radii outside the central disk region at log \( r = 1.4 \) to the virial radius. The obvious interpretation is that the hot gas is sufficiently close to hydrostatic equilibrium.

From a practical point of view, this result gives us a very strong handle on how to set up initial conditions for realistic galaxies for numerical experiments. One should simply use the total density profile (typically dominated by the underlying DM distribution) together with equation (3).

For the comparisons above, we have used \( \gamma = 3/2 \). From the simulations, we naturally have \( \gamma(r) \) in each radial bin from equation (2), and we find that \( \gamma = 3/2 \) is a very good approximation in the entire region considered, namely, \( 1.4 < \log r < 2.4 \). In the figures, we also present the prediction from equation (3) when using the actual value of \( \gamma(r) \) (crosses), and we see that there is very little difference from simply using \( \gamma = 3/2 \).

4.1. Additional Aspects

It is important to test that our findings are robust against different feedback schemes. We have therefore performed four high-resolution simulations of the same galaxy, using different feedback prescriptions, ranging from normal to very low SN feedback (see details in Sommer-Larsen 2006). We do indeed find that our results are robust, since outside 10 kpc there is very little difference between the density and temperature profiles for these four different simulations.

One seemingly disturbing aspect of equation (3) is that if the total density slope becomes more shallow than \(-2\), then the gas density profile gets a positive sign. We find that it is a remarkable conspiracy that the total density profile indeed remains as steep as \(-2\) in the virialized region (see open triangles in the figures).

In the very central region, the gas density is dominated by the cold gas disk. The predictions for a disk profile is different than the predictions for a spherical distribution in equation (3), and the disk prediction is approximately \( d \log \rho / d \log r \approx -2 \), which is in rough agreement with the numerical findings (see open circles for \( \log r < 1.4 \)).

It was suggested that the tangential velocity distribution might have a transition from the inner region to the outer region of the form

\[
v_{\tan} = v_u \left( \frac{r}{r_u} \right)^{\alpha},
\]

where \( \alpha \) should go from unity in the inner region to \(-2\) in the outer region (Hansen & Stadel 2003). We find that the tangential velocity is well fitted with the shape \( v_{\tan} = \exp(-r^{2.3}) \) everywhere in the resolved region. This simply shows that the assumption of a power law for the rotational gas velocity is not good. Furthermore, the gas is approximately in hydrostatic equilibrium and has only a small radial velocity component in the central region where cooling is most important. We hope to investigate the details of the radial velocity and an exponential tangential velocity in the future.
5. CONCLUSIONS

Standard galaxy formation scenarios predict that the central cold gas disk and stars are surrounded by an extended halo of hot gas. We investigate quantitatively the density profile of this gas halo. We find that results of cosmological $\Lambda$CDM $N$-body/hydrodynamical simulations of the formation and evolution of galaxies and analytical solutions to the fundamental gas equations are in remarkable agreement. We find that the gas density slope (the logarithmic derivative) is a nontrivial function of the slope of the total matter, expressed through equation (3). This equation is useful when constructing realistic galaxies for controlled numerical experiments.

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