WHERE ARE THE “MISSING” GALACTIC BARYONS?

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ABSTRACT

Based on 19 high-resolution N-body/gasdynamical galaxy formation simulations in the ΛCDM cosmology, it is shown that for a galaxy like the Milky Way, in addition to the baryonic mass of the galaxy itself, about 70% extra baryonic mass should reside around the galaxy (inside of the virial radius), chiefly in the form of hot gas. Averaging over the entire field galaxy population, this “external” component amounts to 64%–85% of the baryonic mass of the population itself. These results are supported by the recent detection of very extended, soft X-ray emission from the halo of the quiescent, massive disk galaxy NGC 5746. Some of the hot gas may, by thermal instability, have condensed into mainly pressure-supported, warm clouds, similar to the Galactic high-velocity clouds (HVCs). Based on an ultra–high-resolution cosmological test simulation of a Milky Way–like galaxy (with a gas particle mass and gravity softening length of only $7.6 \times 10^3 h^{-1} M_\odot$ and 83 $h^{-1}$ pc, respectively), it is argued that the hot gas phase dominates over the warm gas phase, in the halo. Finally, an origin of HVCs as “leftovers” from filamentary, “cold” accretion events, mainly occurring early in the history of galaxies, is proposed.

Subject headings: cosmology: theory — galaxies: formation — methods: numerical

Online material: color figures

1. INTRODUCTION

In the ΛCDM cosmology, a disk galaxy like the Milky Way will have a virial mass of $\sim 8 \times 10^{11} M_\odot$. For a universal baryon fraction $f_b \sim 0.15$, one would expect the baryonic mass of the Milky Way to be $\sim 1.2 \times 10^{12} M_\odot$, assuming that the bulk of the baryonic material inside of $r_{\text{vir}}$ ($\sim 250$ kpc) is deposited onto the central galaxy. However, the baryonic mass (stars + cold gas) of the Milky Way is found to be just $\sim 6 \times 10^{10} M_\odot$ (e.g., Dehnen & Binney 1998; Sommer-Larsen & Dolgov 2001), so an amount of baryonic mass, as large as the actual mass of the Milky Way itself, appears to be “missing” (e.g., Silk 2004; Maller & Bullock 2004).

On the other hand, on theoretical grounds it has been known for a long time that galaxies (not only in groups and clusters, but also in the “field”) should be embedded in extended halos of hot gas (e.g., White & Frenk 1991; Sommer-Larsen 1991), and evidence of hot, dilute gas in the Galactic halo is strong (e.g., Sembach et al. 2003; McKerman et al. 2004; Wang et al. 2005). Searches for X-ray emission from the halos of external, quiescent disk galaxies have until very recently proved unsuccessful (as opposed to starburst galaxies; e.g., Strickland et al. 2002), and this has been taken as an indication that the baryonic mass of such hot halos is insignificant, due to, e.g., strong AGN-driven hot gas outflows at some point during galaxy formation (e.g., Benson et al. 2000).

Based on recent cosmological simulations of disk galaxy formation (not invoking violent active galactic nucleus [AGN] feedback), however, Toft et al. (2002) showed that the X-ray null detections were to be expected. Moreover, they showed that the X-ray luminosity of disk galaxy halos is expected to be a very steep function of the characteristic circular speed, roughly as $L_X \propto V^7$. Very recently, Pedersen et al. (2006) observed the massive, quiescent, isolated, and edge-on disk galaxy NGC 5746 ($V_c = 305 \pm 7$ km s$^{-1}$), and they detected hot-halo soft ($kT \sim 0.4$ keV) X-ray emission at the level predicted by the numerical models (see also Rasmussen et al. 2005 for more detail). Since the mass of hot gas inside of $r_{\text{vir}}$ for such a galaxy is predicted to be $\sim 0.8$ of that of the central galaxy, and since the total “external” baryonic mass fraction is $\sim 1.1$ (§ 3), it is clearly of interest to estimate the global external baryonic mass fraction, averaged over the entire field galaxy population. This is the aim of this Letter. In § 2 the code and simulations are briefly described, and the results obtained are presented in § 3 and discussed in § 4.

2. 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, hereafter SLGP). The main improvements over the previous version are (1) the “conservative” entropy equation solving scheme (Springel & Hernquist 2002), (2) noninstantaneous gas recycling and chemical evolution, tracing 10 elements (Lia et al. 2002; the algorithm includes supernovae of Type II and Type Ia, and mass loss from stars of all masses), and (3) atomic radiative cooling, depending both on the metal abundance of the gas and on the metagalactic UV field, and modeled after Haardt & Madau (1996), as well as a simplified treatment of radiative transfer, i.e., switching off the UV field where the gas becomes optically thick to Lyman limit photons on scales of $\sim 1$ kpc.

For the present project, the formation and evolution of 15 individual galaxies, known from previous work to become disk galaxies at $z = 0$, were 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 ($z \geq 4$) starbursts (and related Type II supernova–driven energy feedback) found previously to be required, in order to produce realistic disk galaxies. The galaxies were selected to represent “field” galaxies (SLGP) and span a range of characteristic circular speeds of $V_c \sim 100$–330 km s$^{-1}$ ($M_{\text{vir}} \sim 6 \times 10^{10}$–$3 \times 10^{12} M_\odot$).

The dark matter (DM) halos were selected from a cosmological, DM-only simulation of box length $10 h^{-1}$ Mpc, $z_i = 39$, and $(\Omega_\text{m}, \Omega_\Lambda) = (0.3, 0.7)$. The mass resolution and the
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 (SPH) particle according to an adopted universal baryon fraction of $f_{\text{b}} = 0.15$, in line with recent estimates. In this Letter, only results of high-resolution simulations, consisting of at least $1.5 \times 10^5$ SPH+DM particles, will be presented [with typical numbers in the range $(2-3) \times 10^5$]. Comparison to simulations of lower and very high resolution, respectively, will be discussed, though. For galaxies of $V_c < 150$ km s$^{-1}$, $m_{\text{gas}} = m_\text{s} = 9.1 \times 10^4$, and $m_{\text{DM}} = 5.2 \times 10^5 h^{-1} M_\odot$. Moreover, gravitational (spline) softening lengths of $\epsilon_{\text{gas}} = \epsilon_\text{s} = 190$ and $\epsilon_{\text{DM}} = 340 h^{-1}$ pc, respectively, were adopted. For galaxies of $V_c \geq 150$ km s$^{-1}$, $m_{\text{gas}} = m_\text{s} = 7.3 \times 10^5$ and $m_{\text{DM}} = 4.2 \times 10^6 h^{-1} M_\odot$, and $\epsilon_{\text{gas}} = \epsilon_\text{s} = 380$ and $\epsilon_{\text{DM}} = 680 h^{-1}$ pc. In addition, two galaxies of $V_c = 180$ and 244 km s$^{-1}$, respectively, were simulated with the smaller particle masses and gravity softenings above. These very high resolution runs consisted of 1.2 and 2.2 million particles. 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 (SLGP). Finally, in order to enable some reuse of previous work, values of $h = 0.65$ and $\alpha_\text{s} = 1.0$ were employed in the cosmological simulations. These values are slightly different from the values of $h = 0.7$ and $\alpha_\text{s} = 0.9$ currently favored. To check the effect of this, one simulation was undertaken with $h = 0.7$ and $\alpha_\text{s} = 0.9$.

3. RESULTS

Here only “external” baryonic mass fractions are discussed (general simulation results will be presented elsewhere). For each disk galaxy simulation, the distribution of baryonic mass, at $z = 0$ and inside of the virial radius, was classified as follows: (1) disk + bulge stars [$R < 20(V_c/220$ km s$^{-1}$) kpc], $|z| < 5(V_c/220$ km s$^{-1}$) kpc], (2) inner halo stars [$r < 20(V_c/220$ km s$^{-1}$) kpc; not in the above region], (3) stellar satellites/outer halo ($r < r_{\text{vir}}$, and not in the above regions), (4) gas in the galaxy (mainly “cold”: $T \leq 3 \times 10^4$ K; same region as for the disk+bulge stars), (5) outer hot gas ($T > 3 \times 10^5$ K; $r < r_{\text{vir}}$ outside disk+bulge region), and (6) outer cold gas ($r < r_{\text{vir}}$ outside disk+bulge region). The hot gas is typically at $T \sim T_{\text{vir}}$, and hence, in general, much hotter than $3 \times 10^4$ K.

The simple estimate of the galactic baryonic mass would be the combined mass of components 1 and 4. Figure 1 shows, for 19 high-resolution disk galaxy simulations, the mass of the other components relative to this baryonic galaxy mass. Components 3 and 6 have been combined, since most of the “external” cold gas is located in satellite galaxies. As can be seen, the importance of the three resulting “external” components increases with $V_c$ at $V_c \sim 100$ km s$^{-1}$; the external baryonic mass fraction is only about 20%; at $V_c \sim 220$ km s$^{-1}$ (like the Milky Way), this fraction increases to $\sim 70\%$, and at $V_c \sim 300$ km s$^{-1}$, it is about a factor 1.1. At all $V_c$, the hot gas is the dominant external component. To assess the dependence on feedback physics, Figure 2 shows the results of various simulations of three galaxies, run at high resolution, but with different prescriptions for Type II supernova (SN II) feedback. For a small galaxy, of $V_c \sim 110$ km s$^{-1}$, results for four different simulations are shown: two with early, self-propagating star formation (SPSF) and associated strong feedback (for two different threshold densities $n_{\text{H}, \text{crit}} = 0.1$ [resulting in the strongest early feedback] and 0.25 cm$^{-3}$; SLGP), one with early fast star formation but no SPSF (this reduces the early feedback considerably), and one with no early fast star formation at all (this corresponds to the very weak feedback case). Figure 2 shows that (1) the stronger the feedback, the smaller the resulting baryon mass fraction.
fraction inside of the virial radius and that (2) the quantities shown in Figure 1 are quite robust to such a dramatic change of feedback physics (the two lower feedback simulations result in unrealistic disks; hence, they are not included in the analysis). Also shown are data for SPSF simulations, with the above two thresholds, for $V_c \sim 205$ and 305 km s$^{-1}$ galaxies, respectively. As can be seen, these results are quite robust as well.

To test for resolution effects, results for seven galaxies with $V_c$ in the range 170–250 km s$^{-1}$, run at low resolution (the main one of SLGP) and high resolution, but with identical feedback descriptions, were compared. It was found that the hot gas fraction decreased by 28% ± 4%, and the total “external” baryonic mass fraction by 18% ± 6%, increasing the mass resolution by a factor of 8 and the force resolution by a factor of 2. For a single galaxy of $V_c \sim 305$, the corresponding numbers were 23% and 13%. To test the effects of going to very high resolution, results for two galaxies, of $V_c = 180$ and 244 km s$^{-1}$, were compared at $z \sim 1$ and 2, respectively (results at $z = 0$ were not available, but at both redshifts gas cool-out and star formation is very well underway). It was found that in going from high to very high resolution, the hot gas fraction is reduced only by about 5% more, and the total external baryon fraction did not change at all. On the basis of the above-mentioned findings, only simulations run at high resolution were used in the present analysis.

4. DISCUSSION

To estimate the global importance of the external baryons in the mass budget of disk galaxies, the global distribution of disk galaxy circular velocities (the “velocity function”) is required. Galaxy velocity functions have been estimated by, e.g., Gonzalez et al. (2000) and Desai et al. (2004). Most published velocity functions refer to the general morphological mix of disk, lenticular, and elliptical galaxies, in the field or in clusters, but Gonzalez et al. (2000) give an expression for field disk galaxies, viz.,

$$
Ψ_e(V)dV = Ψ_*,\left(\frac{V}{V_*,c}\right)^\beta \exp\left[-\left(\frac{V}{V_*,c}\right)^p\right]dV/V_*,c,
$$

where $Ψ_*,c = (2.0 ± 0.4) \times 10^{-2} h^3$ Mpc$^{-3}$, $\beta = 1.3 ± 0.18$, $n = 2.5$, and $V_*,c = 247 ± 7$ km s$^{-1}$. Next, one has to determine the relation between $V_*$ and the combined baryonic mass of the disk+bulge stars and gas in the galaxy. For the 19 high-resolution simulations, this relation is very well fitted by a power law, $M_\text{gas} = (5.0 \pm 0.1) \times 10^{10}(V_*/220$ km s$^{-1})^{(0.00 \pm 0.07)} M_\odot$. Third, the external baryonic mass fraction, $κ \equiv (M_\text{bar external}/M_\odot)$, is parameterized as a function of $V_*$ by a linear fit to the data shown in Figure 1, resulting in $κ(V_*) = (1.00 \pm 0.07)(V_*/220$ km s$^{-1}) ^{-0.31 \pm 0.02}$. The fit is valid in the range $V_* \sim 100–330$ km s$^{-1}$ and extrapolates to zero at $V_* = 68$ km s$^{-1}$; in the following, $κ = 0$ is assumed for $V_* < 68$ km s$^{-1}$, to obtain a lower limit to the global baryonic external mass fraction (actually, at $V_* \leq 100$ km s$^{-1}$, $κ$ is expected to start increasing with decreasing $V_*$ as SN II feedback increasingly suppresses gas cool-out and star formation: for an $N \sim 3 \times 10^3$ particle simulation of a $V_* = 41$ km s$^{-1}$ galaxy, an external baryon fraction of $\sim 14$% was found).

The globally averaged external baryonic mass fraction can now be expressed as

$$
κ = \frac{\int_0^{V_*,c} ψ_e(V)dV}{\int_0^{V_*,c} M_\text{gas}(V)ψ(V)dV},
$$

where $V_*,c\text{max}$ is the maximum circular speed of disk galaxies. Using equations (1) and (2), and assuming $V_*,c\text{max} = 350$ km s$^{-1}$ (disk galaxies of such circular speeds are certainly observed), $κ = 0.64$ is obtained. Increasing $V_*,c\text{max}$ to 500 km s$^{-1}$ (which must be considered an observational upper limit) results in an increase of $κ$ to 0.72. Fitting to the various external components individually shows that hot gas contributes 70% to $κ$, inner halo stars 5%, and outer halo stars, satellite stars, and cold gas in satellites 25%. Assuming that the above results on external mass fractions also apply to field elliptical/lenticular galaxies (see Fig. 1), and applying the field galaxy velocity function of Desai et al. (2004), increases the estimate of $κ$ to 0.72 and 0.85, for $V_*,c\text{max} = 350$ and 500 km s$^{-1}$, respectively (in principle, very strong AGN feedback, not included in the current simulations, could lower hot gas fractions of E/S0 galaxies; on the other hand, E/S0 galaxies are [contrary to disk galaxies], in general, observed to be embedded in hot gas halos). Finally, since, in particular, the larger galaxies host a number of smaller galaxies within their virial radius, the velocity functions should actually be reduced according to the low $V_*$ end. Hence, the above $κ$ estimates are in fact lower limits.

The above results, taken at face value, provide an explanation as to why only about half of the baryonic mass, inside of the virial radius of galaxies like the Milky Way, is actually found in stars and cold gas in the galaxies. Given the ramifications of this result, it is important to test its robustness, and although $f_r = 0.15$ is indicated by standard big bang nucleosynthesis, by various cosmic microwave background results, and by direct measurements of $f_r$ in galaxy clusters, lower values are still not excluded. To test the effect of adopting $f_r = 0.10$, five galaxies were resimulated with this value, at the resolution of SLGP. The results of these five simulations were compared to a sample of 39 simulations run with $f_r = 0.15$ at the resolution of SLGP. It is found that hot gas fractions, as well as total external baryonic mass fractions, increase by 30%–50% (at a given $V_*$), going from $f_r = 0.15$ to 0.10. This is mainly due to the decreased efficiency of hot gas cool-out and the resulting increase of the virial radius at a given circular speed of the central disk galaxy.

To test the effect of adopting $h = 0.7$ and $σ_0 = 0.9$, rather than $h = 0.65$ and $σ_0 = 1.0$ used in the main simulations, one simulation was run with the former parameters at the resolution of SLGP. Compared to the above 39 simulations, it was found that the hot gas as well as the total external fraction increased by $\sim 5$%–10%. This is likely mainly due to the Hubble time being 7% less, allowing less time for hot gas cool-out.

The hot, dilute halo gas may be susceptible to thermal instability, causing the formation of a two-phase medium consisting of a hot phase ($T \sim 10^6$ K) and a warm phase ($T \sim 10^4$ K) in approximate pressure equilibrium (e.g., Mo & Miralda-Escude 1996; Burkert & Lin 2000; Maller & Bullock 2004; Kaufmann et al. 2005). To estimate this effect for a realistic, cosmological simulation, a very high numerical resolution is required, and the following approach was adopted: for a “standard” high-resolution simulation of a Milky Way–like galaxy ($V_c = 224$ km s$^{-1}$, $M_\text{vir} = 8 \times 10^{10} M_\odot$, $r_\text{vir} = 256$ kpc), at $z = 0.4$, each gas particle, at $r < 300$ kpc, was split into eight equal-mass gas particles, to achieve a very high resolution of the gas phase inside of $r_\text{vir}$. The simulation was then continued for 0.2 Gyr, whence each gas particle, at $r < 50$ kpc, was again split into eight equal-mass gas particles, to achieve an ultrahigh gas-phase resolution in the region where most of the warm clouds reside (see below). The resulting ultra–high-resolution gas particle mass is $7.6 \times 10^3 h^{-1} M_\odot$, and the gravity softening length $l_\text{gas} = 83 h^{-1}$ pc. The simulation was then continued for an additional 0.5 Gyr. In Figure 3, for $r < 50$ kpc, the
distribution of warm cloud masses at $t = 0.3$ and 0.7 Gyr is shown. The integrated warm cloud mass decreases somewhat with time (≈20%) to $\sim 5 \times 10^6 M_\odot$ at $t = 0.7$ Gyr, or about 2% of the total mass of hot-halo gas at $r < 50$ kpc. Also shown is the mass distribution of warm clouds at $r < 50$ kpc in the very high resolution simulation at $t = 0.7$ Gyr. To the cloud resolution limit of this simulation, $M_{\text{cl, res}} \sim 2 \times 10^6 M_\odot$, the agreement between the two simulations is quite good. Moreover, with a resolution limit of $M_{\text{cl, res}} \sim 3 \times 10^5 M_\odot$ for the ultra–high-resolution simulation, the peak at $M_\odot \sim (7–8) \times 10^5 M_\odot$ appears well resolved. Hence, it seems unlikely that the mass contribution from warm clouds of mass less than about $3 \times 10^5 M_\odot$ is significant; such clouds will in any case quickly be destroyed by various physical processes (e.g., Maller & Bullock 2004).

From the very high resolution simulation, the mass in warm clouds at 50 kpc $< r < 256$ kpc is about 75% of that within 50 kpc. Assuming this ratio, the total mass of warm clouds at $r < r_{\text{cr}}$ down to $M_\odot \sim 3 \times 10^5 M_\odot$ is estimated to be $\sim 10^8 M_\odot$.

It seems unlikely that the inclusion of warm clouds of $M_\odot \sim 3 \times 10^5 M_\odot$ (which cannot be resolved by the current simulation) will increase this estimate by more than a factor of a few. Putman (2006) estimates the total gas mass of the HVC system of the Milky Way to be $\sim (4–6) \times 10^8 M_\odot$, assuming that the HVCs are distributed to distances of $\sim 60$ kpc (a reasonable assumption according to the present findings). This is in fair agreement with, although somewhat larger than, the above estimates. Moreover, the hot gas in the halo of the simulated Milky Way–like galaxy has $n_\text{H} \sim 10^{-3}$, $10^{-4}$, and $10^{-4.5} \text{cm}^{-3}$ at $r < 10$, 50, and 100 kpc, respectively. This is in reasonable agreement with the lower limit of $10^{-1} \text{cm}^{-3}$ deduced by Quilis & Moore (2001) from the observed head-tail structure of many Galactic HVCs (also displayed by many of the simulated warm clouds).

The warm clouds are mainly confined by the pressure of the ambient halo gas, although some of the most massive high-density cores and have a ratio of gravitational to thermal energy of about 0.5. Moreover, they typically appear to be seeded by warm filamentary structures, which are leftovers from earlier “cold” accretion (e.g., Birnboim & Dekel 2003; Keres et al. 2005; Sommer-Larsen 2006; details will be given in Putman & Sommer-Larsen 2006). No additional warm clouds appear to form, despite the fact that the necessary condition for onset of thermal instability, viz.,, is satisfied everywhere in the hot-halo gas ($\tau_\gamma$ is the sound crossing time). The mass of hot gas within $r_{\text{cr}}$ is $\sim 2.3 \times 10^8 M_\odot$, so the ratio of warm cloud mass to hot gas mass is at most a few percent. Although fully cosmological simulations at even higher resolution are required to address these issues completely, the above results strongly suggest that the hot gas phase is the dominant one in the halo.

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\(^1\) For images, and an HVC animation, see http://www.tac.dk/~jlsarsen/HVC.