EVIDENCE FOR PROGRESSIVE LOSS OF STAR-FORMING GAS IN SDSS GALAXIES

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Received 2007 October 18; accepted 2008 March 12

ABSTRACT

Using the star formation rates from the SDSS galaxy sample, extracted using the MOPED algorithm, and the empirical Kennicutt law relating star formation rate to gas density, we calculate the time evolution of the gas fraction as a function of the present stellar mass. We show how the gas-to-stars ratio varies with stellar mass, finding good agreement with previous results for smaller samples at the present epoch. For the first time we show clear evidence for progressive gas loss with cosmic epoch, especially in low-mass systems. We find that galaxies with small stellar masses have lost almost all of their cold baryons over time, whereas the most massive galaxies have lost little. Our results also show that the most massive galaxies have evolved faster and turned most of their gas into stars at an early time, thus strongly supporting a downsizing scenario for galaxy evolution.

Subject headings: galaxies: evolution — galaxies: fundamental parameters

Online material: color figures

1. INTRODUCTION

In galaxies, the star formation rates are known to depend on the cold (T < 200 K) gas densities via the well-known empirical Kennicutt (1998, hereafter K98) relation. According to this relation, the star formation rate surface density Σ_istar is proportional to a certain power of the gas surface density Σ_gas according to the relation Σ_istar ∝ Σ_gas^k, where k ≈ 1.4. This relation expresses the natural condition that the star formation rate depends on the amount of gas available; galaxies dominated by young stellar populations have large reservoirs of gas, which can be turned into stars. On the other hand, gas-poor galaxies have consumed their gas in the past and/or have ejected it from its cold state, perhaps into the intergalactic medium, and at the present time they do not exhibit significant star formation. In dense environments, gas can also be stripped, because of interactions with the intergalactic medium or encounters with other systems.

A fundamental quantity related to the gas accretion history of galaxies is the gas-to-stellar fraction (G/S). An important study of this quantity is the one of Kennan and K04, who determined G/S for ~35,000 galaxies from the Sloan Digital Sky Survey (SDSS) and the Two Micron All Sky Survey (2MASS) databases on the basis of photometric techniques. A similar study on a smaller sample of low-mass galaxies has been performed by Geha et al. (2006, hereafter G06). Previous important studies of the evolution of the star formation and gas content in galaxies at low and high redshift are the works by Erb et al. (2006a, 2006b) and Erb (2008).

By means of analytic chemical evolution models, Dalcanton (2007) studied the chemical properties of local galaxies and put some quantitative constraints on their amounts of gas infall and outflow. However, neither of these studies was able to address how infall and outflow vary as a function of the galactic mass.

In the present paper, we start from the SDSS galaxy sample, and by means of the K98 relation and other simple physical assumptions we aim to compute how the gas accretion history of local galaxies depends on their stellar masses. The sample we are considering includes ~310,000 galaxies, larger than the one considered by K04 by a factor of ~9. The strength of our method is that it is based on very few free parameters, whose range of values can be tested very easily, allowing us to draw robust conclusions about some fundamental physical properties of galaxies and on their evolution with cosmic time. We study how the gas mass of these galaxies has varied throughout their evolution and compare our predictions with observational data available in the literature. We focus on the present-day gas fractions and study how these quantities depend on the galactic stellar mass, investigating how the downsizing character of the galaxy populations affects their gas accretion history.

The paper is organized as follows: in § 2, we present the galaxy sample and the MOPED algorithm used for the analysis. In § 3, we describe the methods used to derive the gas masses for the galaxies of the SDSS catalog. In § 4, we present our results, and in § 5 we draw some conclusions. We assume a concordance cosmology with Ω_m = 0.24, Ω_Λ = 0.76 (Spergel et al. 2007), and h = 0.71.

2. SDSS DR3 ANALYSIS WITH MOPED

Following Panter et al. (2007), we select galaxies from the third data release (DR3) main galaxy catalog of the SDSS. In order to remove any bias and simplify our Vmax criterion (where Vmax is the maximum volume of the survey in which the galaxy could be observed in the SDSS sample), we have cut our sample at μ_r < 23.0. The surface brightness cutoff of 23 mag arcsec^{-2} excludes gas-rich, low surface brightness galaxies. However, very gas-rich galaxies are present in our sample, as we see in § 4.1.

At low redshifts, a small number of Sloan galaxies are subject to shredding, in which a nearby large galaxy is split by the photometric pipeline into several smaller sources. Shredding affects a negligible number of galaxies for 0.01 < z < 0.25; for z < 0.01 it could be as many as 10% of galaxies. (SDSS Collaboration 2007, private communication). We have chosen to make a conservative cut at z = 0.02 to avoid this problem. This also removes the problem of non–Hubble-flow peculiar velocities giving erroneous distances based on redshift, which can have a
significant effect on recovered stellar mass and metal return. The total number of galaxies that satisfy our cuts is 299,571.

In order to estimate the completeness of the survey, we have used the ratio of target galaxies to those that have observed redshifts (P. Norberg 2007, private communication). This does not allow for galaxies that are too close for the targeting algorithm, and we estimate this fraction at a 6% level from the discussion in Strauss et al. (2002). As a result of both these cuts, our effective sky coverage is 2947 deg$^2$. We also removed from our analysis a set of wavelengths that may be affected by emission lines that are not modeled by the stellar population codes.

We use the 3 Å single-stellar population models of Bruzual & Charlot (2003) as the basis for this study, but we emphasize that the star formation histories allowed are very flexible. We assume an initial mass function (IMF) given by Chabrier (2003), which is very successful at reproducing current observations in our galaxy. We chose to apply a uniform velocity dispersion of 170 km s$^{-1}$ to the 3 Å models, reflecting a typical value for the main galaxy sample. Although a velocity dispersion of 170 km s$^{-1}$ is too large to represent the smallest mass galaxies in the sample, this discrepancy does not affect any of our results.

Physical parameters of galaxies have been derived from their observed spectra by means of the MOPED algorithm (Heavens et al. 2000; Reichardt et al. 2001). As with previous MOPED studies, for this analysis we have used a single foreground dust screen. We chose to use an LMC extinction law for the main analysis, as given in Gordon et al. (2003).

2.1. Recovering Star Formation and Metallicity History using MOPED

In the past, the star formation history (SFH) of galaxies was typically modeled by an exponential decay with a single parameter; for more complex models one or two bursts of formation were allowed. In fact, it would be better not to put any such constraints on star formation, particularly considering that each galaxy may have (as a result of mergers) several distinctly different aged populations. Star formation takes place in giant molecular clouds, which have a lifetime of around 10$^7$ yr. Splitting the history of the universe into the lifetimes of these clouds gives a natural unit of time for star formation analysis, but unfortunately it would require several thousands of these units to map the age of galaxies formed 13 billion years ago, and the lack of sensitivity of the final spectrum to the detailed history would make any estimate of star formation history extremely degenerate. We choose a compromise solution that allows 11 time bins in which the star formation rate (SFR) can vary independently. This is still a difficult computational problem, but the MOPED (Heavens et al. 2000) algorithm reduces processing time to approximately 1 minute per spectrum on a standard workstation. The boundaries between the 11 different bins used are determined by considering bursts of star formation at the beginning and end of each period (at a fixed metallicity), and we set the boundaries such that the fractional difference in the final spectrum is the same for each bin. This leads to a set of time bins $t_i$ that are almost equally spaced in log(t look-back time). Nine time bins are spaced with a ratio of log(t look-back time) of 2.07 in this application of MOPED, plus a pair of high-redshift bins to improve resolution at $z > 1$. The central ages for the time bins $t_i$ are 0.0139, 0.0288, 0.0596, 0.123, 0.256, 0.529, 1.01, 2.27, 4.70, 8.5, and 12.0 Gyr. Single-value decomposition analysis of SDSS spectra, as suggested by Ocvirk et al. (2006), indicates that only 2--5 components can be reliably recovered, not 11, but MOPED in fact recovers ≤5 significant components in 98% of cases (Tojeiro et al. 2007).

The gas that forms stars in each time bin is also allowed to have a metallicity that can vary independently. Extensive testing (Panter et al. 2003, 2007) shows that for large samples the average star formation history is recovered with good accuracy. The Bruzual & Charlot (2003) models allow metallicities in the range 0.02 < $(Z/Z_\odot)$ < 1.5. In order to investigate metallicity evolution (Panter et al. 2007), no regularization or other constraint is applied to the metallicity of the populations; each different age can have whatever metallicity fits best. A further complexity in the parameterization dealing with postmerger galaxies that contain gas that has followed dramatically different enrichment processes would be to have several populations with the same age but independent metallicities. It is possible to consider a more complex parameterization, but again one risks degeneracies in solution. With 11 ages, 11 metallicities, and the dust parameter, the model has 23 parameters. The 23 dimensional likelihood surface is explored by a Markov chain--Monte Carlo technique outlined in Panter et al. (2003). Further information on the MOPED algorithm is contained in Panter (2005).

We take account of the 3′ fiber aperture by correcting the spectrum upward by the ratio of the $r$-band Petrosian flux in the photometric survey to the $r$-band flux received by the fiber. Although for individual galaxies this is likely to fail, for the population as a whole there is evidence from the colors (Glazebrook et al. 2003) that there is no overall bias between the sampling of stellar populations by the spectroscopy and photometry.

3. DERIVATION OF THE GAS MASSES

The MOPED algorithm allows us to determine the star formation history of each galaxy, i.e., the star formation rate values at the end of the 11 time bins described above. For each time bin, we aim to determine the cold gas mass of any galaxy on the basis of its SFR by inverting the K98 relation, which links the gas surface density to the SFR per unit area. A similar technique was used by Erb et al. (2006a) and Erb (2008) to derive the gas fractions for a sample of star-forming galaxies at $z \sim 2$ and to study the implications of the mass-metallicity relation observed at high redshift on the galactic gas accretion history, respectively.

Following K98, for any galaxy and at a given time, the gas surface density $\Sigma_{gas}$, expressed in $\text{M}_\odot$ pc$^{-2}$, depends on the SFR surface density $\Sigma_{sfr}$, expressed in $\text{M}_\odot$ yr$^{-1}$ pc$^{-2}$ according to

$$\Sigma_{gas} = \left( \frac{\Sigma_{sfr}}{2.5 \times 10^{-4}} \right)^{0.714} \text{M}_\odot \text{ pc}^{-2}. \quad (1)$$

The MOPED catalog provides the deprojected SFRs in units of $\text{M}_\odot$ yr$^{-1}$; hence, to derive the corresponding surface densities, we need an estimate of the galactic scale-length radius as a function of the baryonic mass. We calculate this quantity by means of the scaling relations by Mo et al. (1998), and we follow its evolution with look-back time. A major difference between the works by Erb et al. (2006a) and ours mainly concerns our detailed study of the scaling radius as a function of mass and redshift.

For each galaxy, we know the present-day stellar mass $M_*$, whereas the scale length is likely to be set principally by the total mass. We assume that each galaxy is embedded inside a dark matter halo of mass $M = M_* f$, where $f$ is a parameter that we take to be a constant. The value of $f$ and its dependence on mass and time are, in a sense, part of what we are trying to obtain, but here we use $f$ only to set the scale length of the galaxy. As we see later, this assumption for $f$ has a minor impact on our results.

Initially, we make the assumption (relaxed later) that the baryons collapse into a disk, which is assumed to be thin and in
centrifugal balance, with an exponential surface density profile \( \Sigma_{\text{rot}}(R) = \Sigma_0 \exp(-R/R_d) \), where \( \Sigma_0 = \Sigma_{\text{gas}} + \Sigma_* \) is the central density of the disk, and an angular momentum that is a fraction \( f \) of the angular momentum of the dark matter halo.

For the halo, we assume a Navarro et al. (1997) mass profile, and we take into account the effects of the self-gravity of the disk. For each halo of mass \( M \), the virial radius \( R_{200} \) is defined as

\[
R_{200} \equiv \frac{V_e}{10H(z)},
\]

where

\[
V_e \equiv [10G MH(z)]^{1/3},
\]

where \( G \) is the gravitational constant and \( H(z) \) is the Hubble parameter as a function of the redshift \( z \), given by

\[
H(z) = H_0 \left[ \Omega_\Lambda + (1 - \Omega_\Lambda - \Omega_m)(1 + z)^2 + \Omega_m(1 + z)^3 \right]^{1/2},
\]

where \( \Omega_m, \Omega_\Lambda, \) and \( H_0 \) are the matter density parameter, the vacuum energy parameter, and the Hubble constant at \( z = 0 \).

The scaling radius \( R_d \) can be calculated as (Mo et al. 1998)

\[
R_d = \frac{\lambda R_{200} f_{\text{c,vir}}^{1/2} f_K(\lambda, c_{\text{vir}}, f_\delta)}{\sqrt{2}},
\]

where \( \lambda \) is the spin parameter of the halo and depends on the total energy of the halo \( E \), its angular momentum \( J \), and its mass \( M \) according to

\[
\lambda = J/E^{1/2}G^{-1}M^{-5/2}.
\]

The gas density surface of the halo is then determined by the K98 relation, and the gas mass \( M_{\text{gas}} \) (in \( M_\odot \)) is given by

\[
M_{\text{gas}} = \Sigma_{\text{gas}} (2\pi R_d^2).
\]

In \( \S \).4.1, we relax the assumption of an exponential disk profile and show how the assumptions of a different surface density profile and of different scaling relations affect the calculated galactic gas masses.

At this stage, we can see how the calculated gas mass \( M_{\text{gas}} \) depends on the baryonic fraction \( f \). The quantity \( R_d/R_{200} \) as a function of \( f \) has been calculated by Somerville et al. (2008) and can be fitted by an exponential function \( R_d/R_{200} = 0.77 \exp(-4.7f) \). The dependence of \( M_{\text{gas}} \) on \( f \) is then approximately

\[
M_{\text{gas}} \propto \exp(-2.7f)/f^{0.19}.
\]

The dependence of the resulting gas masses on \( f \) is hence very weak, as a result of which any reasonable estimate for \( f \) will suffice.

In setting the scale length, we take \( f = 0.06 \), in agreement with the recent results of Hoekstra et al. (2005), based on the weak-lensing signals of isolated galaxies at low redshift. This is also consistent with most of the cold baryons being in stellar form. Several recent cosmic baryon budget calculations (Calura & Matteucci 2004; Fukugita & Peebles 2004; Shankar et al. 2006) support this hypothesis, in particular for spiral disks and spheroids.

A potential difficulty of our study is that the analysis above assumes that the galaxy remains a single structure during its history, whereas the star formation history deduced from the fossil record makes no statement about where the stars were when they were formed. Hence, a natural question to ask is how the possible presence of merging affects these results. However, if we assume the scaling relation \( R_d \propto M_1^{0.3} \) holds for any subunits before merging, the final gas-to-star ratio is almost independent of the amount of merging that has taken place. To see this, let us assume that at some look-back time the observed galaxy was in several pieces \( i = 1, \ldots, n \), each containing a fraction \( f_i \) of the final stellar mass. If we assume the star formation rate is proportional to \( f_i \), then the gas mass in each subunit is proportional to \( (\psi_i/R_d^2)^{0.714} R_d^2 \propto f_i^{0.9} \), so the total gas mass is modified to

\[
M_{\text{gas}} \rightarrow M_{\text{gas}} \sum_{i=1}^{n} f_i^{0.9}.
\]

Since \( \sum_i f_i = 1 \), we see that for any reasonable merging history, the gas mass is virtually unchanged. The assumptions we make here are certainly challengeable, but this calculation gives us confidence that the results are likely to be robust to the merger history.

4. RESULTS

4.1. The Evolution of the Gas-to-Stellar Mass Fractions

In this section, we present how the gas accretion history (i.e., the infall history) of our galaxies evolved with cosmic time. In \( \S \).4.2, we present how the outflow history of our galaxies evolved with cosmic time and with galactic mass.

One way to study the evolution of the gas accretion history is to analyze the evolution with mass and with cosmic time of the gas-to-stellar mass ratio (G/S). In Figure 1, we show the evolution...
of G/S calculated as described in § 3, as a function of the stellar mass for the MOPED galaxies at various look-back times. The dispersion of the calculated G/S is relatively small at a look-back time of 12 Gyr. The dispersion, however, remains large (the individual G/S values span 6 orders of magnitude) up to the present time. At any look-back time, the average G/S ratio decreases as the stellar mass increases in the range $10^8 M_\odot < M_\star < 10^{12} M_\odot$. Note that the highest mass bins ($M_\star > 10^{12} M_\odot$) are characterized by a very few systems with a peculiar behavior. In the last Gyr of evolution, our predictions indicate an increase in the average G/S ratios for the galaxies with stellar masses $M_\star < 10^{10} M_\odot$, due to the fact that these galaxies must have accreted gas at late times.

The anticorrelation between G/S and stellar mass found at any look-back time can be interpreted in the following way. In general, higher mass galaxies are more efficient at turning gas into stars, and lower mass galaxies are less efficient and so retain a large amount of their primordial gas. This is clearly visible also in Figure 2, where we show the evolution of G/S as a function of look-back time for several mass bins. In this figure, it is clear that the slope of the curves steepens from low-mass to high-mass systems, indicating decreasing gas consumption timescales from dwarf to giant galaxies. This behavior agrees with the downsizing picture of galaxy evolution, according to which the least massive systems formed the bulk of their stars (consuming most of their gas reservoirs) at recent times, whereas in the most massive galaxies the buildup of the stellar mass was completed several Gyr ago.

At the present time, we predict individual log (G/S) values between −4 and −1.5. This range of values agrees with existing local observational estimates for galaxies of various morphological types. The lowest estimates of G/S have been derived for local dwarf spheroidal galaxies and for large ellipticals. The gas-poorest dwarf spheroidal galaxies of the Local Group have upper limits on the atomic H-to-blue luminosity ratio of $M_{H_\alpha}/L_B < 0.001$ (Mateo 1998). These values correspond to log (G/S) $\approx -3.67$, assuming a helium correction factor of 1.4 and a stellar mass-to-light ratio of $(M/L)_B = 6.5 M_\odot/L_\odot$ (Fukugita et al. 1998, hereafter FHP98). In local S0 and E galaxies, Sansom et al. (2000) observed values of $M_{H_\alpha}/L_B$ down to $\approx 0.0001 M_\odot/L_\odot$, corresponding to log (G/S) $\approx -4.67$.

On the other hand, the largest gas reservoirs are observed in local irregular galaxies. Hunter & Elmegreen (2004) find for local irregulars $M_{H_\alpha}/L_B$ up to $\approx 5 M_\odot/L_\odot$, corresponding to log (G/S) $\approx -0.8$, assuming a helium correction factor of 1.4 and a stellar mass-to-light ratio of $(M/L)_{B,ir} \approx 1 M_\odot/L_\odot$ (FHP98).
These observational estimates are in very good agreement with the lower and upper extremes of the G/S values that we derive for present-day galaxies.

All our calculations have been performed by assuming the same scaling relations for all galaxies; i.e., we have assumed that all our galaxies are self-gravitating disks, embedded in dark matter halos. This assumption may seem unrealistic, since spheroids are characterized by a Sersic surface density profile, and follow the scaling relations derived from disk galaxies. To tackle this problem, we have divided our galaxy sample into two categories, the first composed of disk galaxies, the second of spheroids. Disk galaxies follow the scaling relations described in § 3. For spheroids, instead of an exponential surface mass density profile, we have assumed a Sersic law given by

\[
\Sigma_{\text{sph}}(R) = \Sigma_0 \exp\left(-b_n\left(\frac{R}{R_{\text{eff}}}\right)^{1/n} - 1\right)
\]

(Sersic 1968), where \(b_n \simeq 2n - 0.324\) (Ciotti & Bertin 1999). We want to test two possible values for the index \(n\), namely, \(n = 4\), corresponding to the de Vaucouleurs (1948) law, and \(n = 2\), since most galaxies do not fit into the binary de Vaucouleurs or exponential disk categories, but instead span some range of Sersic parameters (Blanton et al. 2003).

In this case, for the SFR surface density profile, we have assumed that \(\Sigma_{\text{sfr,sph}}(R) \propto \Sigma_{\text{sph}}(R)^{1.4}\). To compute the effective radius \(R_{\text{eff}}\), we have used the Shen et al. (2003) relation between \(R_{\text{eff}}\) and \(M_*,\)

\[
R_{\text{eff}} = 4.16 \left(\frac{M_*}{10^{11} M_\odot}\right)^{0.56} \text{kpc}
\]

(see also Boylan-Klochin et al. 2005; Robertson et al. 2006), valid at any look-back time.

The distinction between disks and spheroids was made by means of two criteria: (1) the stellar mass of the galaxy and (2) its present-day SFR. The first criterion seems plausible, since it is known that at low redshift early-type galaxies have stellar masses higher than late types and that the mass function of galaxies at stellar masses \(M_* < 10^{11} M_\odot\) and \(M_* \geq 10^{11} M_\odot\) is dominated by late types (i.e., disks) and early types (i.e., possibly spheroids; Pannella et al. 2006; Shankar et al. 2006), respectively. On the basis of this, we have computed the gas masses assuming that all the galaxies with \(M_* < 10^{11} M_\odot\) obey the scaling relations described in § 3, whereas all the galaxies with stellar mass \(M_* \geq 10^{11} M_\odot\) are characterized by a Sersic surface density profile, given by equation (11), and follow the scaling relation of equation (12). We are aware that this criterion prevents us from adopting the appropriate profile for low-mass early-type galaxies, such as dwarf spheroidals and dwarf ellipticals. For this reason, we consider an alternative criterion for the distinction between disks and spheroids, based on the SFR.

In the second case, we have assumed that the galaxies with a present-day SFR lower than a given threshold (we have used a threshold value of 0.5 \(M_\odot\) yr\(^{-1}\)) and that have assembled more than 50% of their total stellar mass during the first time step belong to the category of spheroids, whereas the rest are spiral disks. In Figure 3, we show the present-day gas-to-stellar mass ratio as a function of the stellar mass for the MOPED galaxies, computed with the same default scaling relations for all galaxies (filled circles), using different scaling relations for spheroids and spirals, first, disentangling by means of the stellar mass (filled squares; see text for details) and second by means of the current SFR, assuming the Sersic indices \(n = 4\) (open circles) and \(n = 2\) (triangles). [See the electronic edition of the Journal for a color version of this figure.]

In any case, we obtain gas masses and gas fractions very similar to the ones obtained assuming the same scaling relations for all the galaxy population. The same situation occurs at larger look-back times; i.e., at any redshift, the gas masses computed in the...
three cases are very similar. This indicates that our results are fairly independent of the adopted profile. Motivated by this fact, all the results presented in the remainder of the paper have been obtained by adopting the same disk scaling relations for the whole galaxy sample.

At this point, our aim is to understand how our estimates of the scaling radii performed by means of the exponential profile compare with the optical radii of the SDSS galaxies, determined from the observed light profiles. In the left panel of Figure 4, we show the computed scaling radii as a function of the $r$-band Petrosian radii $R_p$ for the SDSS sample; overplotted with the mean are $\pm 1 \sigma$ errors. In Figure 4, the darkest regions correspond to the densest areas, where most of our galaxies lie. This figure shows that for the bulk of the galaxies and for radii $\leq 8$ kpc, there is almost a 1:1 correspondence between scaling radii and Petrosian radii. The scaling radii underestimate the optical radii for $R_p \geq 8$ kpc. The reason for this discrepancy may be found in the right panel of Figure 4, where we show the expected angular size, computed from the scaling radii, against the actual angular size on the sky for the SDSS galaxies. From this plot, we can see that the deviations are larger when the size on sky is very small or very large, and that this discrepancy concerns the minority of the galaxies; hence, it is not a major cause of concern. The match between scaling radii and Petrosian radii seem problematic when the galaxy radius is $<4'$ and $>18'$; otherwise, there is a very good agreement. For a limited number of galaxies, the underestimation of the actual size may imply an underestimation of the gas fractions.

Galaxies of the SDSS sample have been shown to split into two different populations, one composed of blue galaxies dominated by recent star formation episodes and another composed of red, passively evolving early types (Strateva et al. 2001; Blanton et al. 2003). In Figure 5, we show the calculated present-day G/S values as a function of the stellar mass for these two different galactic populations, compared to the corresponding observational estimates by K04. The estimates by K04 are based on photometric techniques. The atomic G/S values are estimated using the $u-K$ colors of $\sim 35,000$ galaxies from the SDSS DR2 and 2MASS databases. This technique is calibrated by means of H i data from the HyperLeda H i catalog. By means of her technique, K04 estimated individual log(G/S) values between $\sim -2$ and $\sim 0.5$. The G/S estimates are very reliable in the lowest mass bins, but trend to represent overestimations in the largest mass bins (S. Kannappan 2007, private communication). For this reason, here we compare the average G/S values computed considering only the galaxies with log(G/S) $> -2$.

By comparing our results with the ones of K04, we are able to obtain constraints on the epoch at which galaxies of the blue and red populations assembled the bulk of their stars. In particular, we can reproduce very well the data obtained by K04 if we assume that the red population consists of all the galaxies that have formed $>60\%$ of their present-day stellar mass during the first four time steps, i.e., in $\sim 11.4$ Gyr. The overall agreement between our estimations and the observational estimates by K04 is good for all galaxies with stellar masses log($M_*/M_\odot$) $\leq 11.$
For the most massive galaxies of the red population, we tend to underestimate the gas fractions. This is not surprising, since as stated above, the estimates by K04 are likely to represent overestimations of the actual values, in particular in the highest mass bins. For the most massive galaxies of the blue population, we predict mean G/S higher than the ones determined by K04 because of the fact that highest mass bins contain very few galaxies, some of which present very high gas fractions, considerably increasing the average G/S in these bins.

The study by B. Panter et al. (2008, in preparation) shows that it is possible to split the SDSS galaxies into two populations on the basis of their color excess $E(B-V)$, which expresses the amount of dust present in any galaxy. To disentangle the blue and the red galactic populations, we tested this criterion also. In this case, the red and blue components are the galaxies with $E(B-V) < 0.01$ and $E(B-V) > 0.01$, respectively. In Figure 6, we present the predicted mean G/S values for the red and blue galaxy populations as compared to the observational data by K04, having determined the distinction between the two populations by means of their color excess $E(B-V)$. The separation of blue and red appears less clear than in the former case. Furthermore, the agreement between our predictions and the data by K04 is worse than the one shown in Figure 5. In fact, in the case of Figure 6, the observed G/S values are systematically underestimated by our predictions, in particular the data for the blue galaxy population. This shows that the color excess is not a totally reliable diagnostic for disentangling blue and red galaxies, being strongly dependent on the inclination causing overlapping between the two different populations (Calzetti 2001).

To conclude this section, we compare our results for the estimated gas fractions with some individual cases of the sample studied by Geha et al. (2006). G06 studied the gas content for a sample of low-luminosity dwarf galaxies selected from the Sloan Digital Sky Survey. This sample consists of 101 galaxies, for which they obtained follow-up H I observations using the Arecibo Observatory and Green Bank Telescope. Using the measured masses of H I and the optical properties, G06 derived the H I-to-stellar mass ratio $M_{\text{HI}}/M_*$ for the galaxies of their sample.

We have identified 23 galaxies from our sample that are also present in the G06 sample. For these 23 galaxies, we compare our values for the stellar masses and $M_{\text{HI}}/M_*$ to the values found by Geha et al. (2006) by a different technique. The results of this comparison are shown in Table 1. For each galaxy, we derive the quantities $M_{\text{HI}}$, by multiplying the gas mass $M_*$ by the solar photospheric H I mass fraction $X_\odot = 0.75$ (Lodders 2003).

In some cases, the stellar-mass values estimated by means of the MOPED algorithm differ from the values reported by G06. These differences may be due to several factors, such as the assumption of a different IMF (G06 use the IMF by Kroupa et al. 1993) and uncertainties in the distances because of peculiar velocities. G06 do not present any uncertainty for their determined stellar masses. For 11 out of 24 galaxies, the discrepancies between our $M_{\text{HI}}/M_*$ values and the ones found by G06 are within 0.7 dex, corresponding to a factor of 5. In 10 cases, we severely underestimate the $M_{\text{HI}}/M_*$, and in the few remaining cases, we overestimate the results by G06 by a factor larger than 5. The very low $M_{\text{HI}}/M_*$ that we obtain in some cases may be due to underestimated galaxy dimensions or to the presence of infalling gas not taking part in star formation, as observed for the local Sculptor dwarf spheroidal galaxy (Carignan et al. 1998). However, most likely it is an indication of the fact that MOPED cannot determine precisely the star formation history of individual galaxies but of ensembles of them, and only for large numbers are the errors very small (see also Fig. 8). There is, however, another trend worth pointing out: those galaxies for which we find the best agreement in the Geha sample are the ones that show the strongest absorption lines, thus providing MOPED with a better way to recover the star formation history, while those that give the worse agreement do have only emission lines (recall

| NAME                | $\log(M_*)$ | $\log(M_{\text{HI}}/M_*)$ | $\log(M_*)$ | $\log(M_{\text{HI}}/M_*)$ | $\sigma_{\text{HI}}$ |
|---------------------|-------------|-----------------------------|-------------|-----------------------------|------------------------|
| 386141               | 6.95583     | 0.47055                     | 7.82000     | 0.26000                     | 0.08                   |
| 192563               | 7.83769     | 0.11271                     | 7.96000     | 0.82000                     | 0.04                   |
| 192971               | 8.05618     | -0.81446                    | 8.00000     | 0.52000                     | 0.05                   |
| 190632               | 8.28466     | -2.06788                    | 8.32000     | 0.46000                     | 0.03                   |
| 677002               | 8.06461     | -2.74395                    | 8.85000     | 0.33000                     | 0.08                   |
| 47936                | 8.41572     | -0.59873                    | 8.51000     | 0.26000                     | 0.06                   |
| 222989               | 8.08221     | -0.00197                    | 8.10000     | 0.63000                     | 0.06                   |
| 203478               | 7.88343     | -0.07654                    | 8.17000     | 0.40000                     | 0.03                   |
| 191112               | 7.44543     | -0.89164                    | 7.66000     | 0.38000                     | 0.07                   |
| 48406                | 8.22616     | -0.58562                    | 8.30000     | -0.32000                    | 0.12                   |
| 231588               | 7.62681     | 0.12001                     | 7.59000     | 0.67000                     | 0.07                   |
| 227294               | 7.36842     | -1.51760                    | 7.77000     | 0.11000                     | 0.07                   |
| 462731               | 6.85259     | 0.89671                     | 7.55000     | 0.26000                     | 0.08                   |
| 467776               | 8.15761     | -0.59137                    | 8.09000     | 0.10000                     | 0.09                   |
| 123408               | 7.92148     | -0.22780                    | 8.09000     | -0.28000                    | 0.08                   |
| 132909               | 7.32389     | 0.11341                     | 7.61000     | 0.65000                     | 0.09                   |
| 136373               | 7.35887     | -2.07113                    | 7.84000     | -0.31000                    | 0.09                   |
| 276603               | 7.92763     | -1.07278                    | 7.72000     | 0.53000                     | 0.07                   |
| 232890               | 7.59235     | 0.02063                     | 7.78000     | 0.42000                     | 0.07                   |
| 169071               | 6.63464     | 0.06289                     | 7.43000     | -0.38000                    | 0.20                   |
| 278622               | 7.53275     | 0.33543                     | 8.07000     | 0.06000                     | 0.08                   |
| 262647               | 6.67881     | 1.05205                     | 7.86000     | -0.30000                    | 0.14                   |
| 565755               | 7.39599     | -3.14264                    | 7.96000     | 0.29000                     | 0.11                   |
that we model only the continuum and absorption lines with MOPED).

4.2. Fractions of Lost Baryons in SDSS Galaxies

In galaxies, gas can be both transformed into stellar form and ejected into the external environment, i.e., the intergalactic (IGM) or intracluster media (ICM). Gas can be ejected by galaxies by means of various processes. Supernova (SN) explosions heat the interstellar gas and, as soon as the binding energy of the gas exceeds its thermal energy, some fraction of the intergalactic medium (ISM) can be removed through SN-driven galactic winds (e.g., Larson 1974). In general, isolated galaxies eject gas mostly by means of galactic winds. Galaxies in dense environments (i.e., clusters and groups) undergo gas loss via additional mechanisms, which in general are bound to environmental effects and can be of various types: tidal interactions, ram pressure stripping, viscous stripping, starvation, and thermal evaporation (see Boselli & Gavazzi 2006 and references therein). In this section, we aim to study how the total amount of cold gas ejected by means of any mechanism evolved with cosmic time. Our approach does not allow us to infer which are the main mechanisms driving gas ejection, for which more complex dynamical simulations or galactic chemical evolution models would be suited when SN feedback is taken into account (Matteucci 1994; Recchi et al. 2002).

To perform this task, once again we use the 11 time bins described in § 2.1. For each galaxy, at each time bin \( t_i \) we know the total baryonic mass \( M_{\text{tot}}(t_i) = M_\text{gas}(t_i) + M_\text{star}(t_i) \). We can compute the net ejected (or accreted) mass as the difference between the total baryonic mass computed at two following time steps \( t_{i-1} \) and \( t_i \): \( M_\text{ej} = M_{\text{tot}}(t_i) - M_{\text{tot}}(t_{i-1}) \). This quantity may be positive or negative, with the negative results indicating mass loss. Note that gas that is heated to the extent that it does not take part in star formation is counted as ejected, regardless of whether it is physically removed from the galaxy or not. We can use this information to compute the complete mass outflow histories for the galaxies of our sample. When baryons are lost or accreted, the total mass of the galaxy goes down, which puts it in a different mass bin. The current stellar mass of a galaxy depends on the star formation history of that galaxy, which is used here to determine the infall and outflow history.

In Figure 7, we show the computed evolution of the mean fraction of lost baryons \( f_{\text{lost}} \), defined as \( f_{\text{lost}} = M_\text{ej}/(M_\text{gas} + M_\text{star}) \), as a function of the stellar mass for the SDSS catalog. With one exception, these curves show a very consistent picture of progressive baryon loss over time for all but the most massive galaxies, with the lowest mass systems losing much more baryon mass than the high-mass systems. The exception to this is the curve at a look-back time of 1.1 Gyr, which is anomalous. The reason for this is almost certainly connected with the difficulty of determining the star formation rate for this population, as nowhere in the spectrum is the population dominant (Mathis et al. 2006).

The mean \( f_{\text{lost}} \) values computed for large galaxies [log \((M_\odot/M_\odot)/11\)] do not show a strong evolution with time, remaining at the low level of \(-10\% - 20\%\). Combined with the G/S ratio for these systems, we conclude that early star formation is very efficient in these galaxies.

On the other hand, the mean \( f_{\text{lost}} \) values computed for galaxies in the range \( 7 \leq \text{log}(M_\odot/M_\odot)/11 \) undergo a strong evolution with look-back time, indicating that the galaxies of lowest mass are continually losing baryonic mass from the cold phase over a long period. This result confirms the predictions from chemical evolution models for elliptical galaxies (Matteucci 1994), which showed that, in order to explain the increase of the [Mg/Fe] ratio with galactic mass, one has to assume that the efficiency of star formation is an increasing function of the galactic mass. One possibility for this is an inverse-wind scenario of galaxy evolution, in which the most massive galaxies are the first ones to experience the galactic winds and to complete their outflow and star formation history, whereas the dwarf galaxies undergo substantial outflows and continuous star formation until the most recent times.

As one would expect from the depths of the potential wells, we find very clear evidence that at the present day the lower mass galaxies have lost a larger fraction of their cold baryons, as much as 90% for galaxies with a stellar mass of \( 10^6 M_\odot \). An analytical fit to the present-day \( f_{\text{lost}}-M_\star \) relation is

\[
f_{\text{lost}} = 0.58 - 0.51 \arctan\left(0.31 \left[ \log\left(\frac{M_\star}{M_\odot}\right) - 9.0 \right] \right),
\]

valid for \( 6 \leq \text{log}(M_\star/M_\odot)/12.5 \). An increasing trend of the ejected fractions with decreasing galactic mass is also confirmed by analytical and numerical single-burst models for dwarf galaxies (Mac Low & Ferrara 1999). Our results are in good agreement with results from galactic chemical and chemodynamical models considering more complex star formation histories. By means of chemodynamical simulations, Recchi et al. (2002) showed that a dwarf galaxy of baryonic mass of \( \sim 10^7 M_\odot \) undergoing multiple starbursts can eject up to \( \sim 75\% \) of its mass. Chemical evolution models for elliptical galaxies of masses between \( 10^{10} \) and \( 10^{12} M_\odot \) predict decreasing ejected fractions, with values between 90% and 10% (Gibson & Matteucci 1997; Pipino et al. 2002).

The shape and normalization of the present-day \( f_{\text{lost}} \) versus \( M_\star \) curve derived observationally in this study is in good agreement
with theoretical predictions from chemodynamical models in which only supernova feedback has been employed. While we cannot rule out that active galactic nucleus (AGN) feedback may also play a role with the present observations, it seems that supernova feedback alone is not sufficient to explain the observed amount of cold gas from the dark halo as a function of mass. This study does not exclude preheating (Mo et al. 2005; Crain et al. 2007), which prevents accretion of gas, but rather provides evidence of some process that has ejected gas from the cold phase after acoustic shock.

Finally, in Figure 8 we show the plot of lost gas versus G/S for all the dwarf galaxies of our sample. In this case all the galaxies with M_\star \leq 10^9 M_\odot have lost gas. The small filled squares are the points for all the galaxies, whereas the large squares are the mean values, plotted with the error bars. The larger, shaded area and the smaller, dotted area indicate the regions where 100% and 85% of the dwarf galaxies of the sample by Geha et al. (2006) lie, respectively. [See the electronic edition of the Journal for a color version of this figure.]

5. CONCLUSIONS

In this paper, we used the Kennicutt relation (K98), linking the surface star formation rate to the gas mass surface density, together with the scaling relations by Mo et al. (1998), linking the galactic scale-length radius to the baryonic mass, to recover the gas mass for ~310,000 galaxies of the SDSS DR3 sample. Our main conclusions can be summarized as follows:

1. We studied the time evolution of the gas-to-stellar mass fractions for all the galaxies of the SDSS catalog. In the last Gyr of evolution, our predictions indicate an increase in the average G/S for the galaxies with stellar masses M_\star < 10^{10} M_\odot in agreement with the downsizing picture of galaxy evolution, where the most massive galaxies form the bulk of their stars at early times. At present, we predict individual log (G/S) values between ~4 and ~1.5. These lower and upper limits agree with independent estimates of G/S in the local gas–poorest and –richest galaxies, respectively.

2. We split the galaxy sample into a red and a blue population by means of two different criteria, i.e., the recent amount of star formation and the color excess E(B–V). The G/S values calculated by adopting the first criterion are in good agreement with independent estimates based on photometric techniques (K04), in particular for the galaxies with stellar masses log (M_\star /M_\odot) \leq 11. The adoption of the color excess criterion implies instead a less clear distinction between the two galactic populations.

3. We computed the time evolution of the average fraction of lost baryons f_{\text{lost}} defined as f_{\text{lost}} = M_{\text{lost}}/(M_\star + M_{\text{gas}}) as a function of the stellar mass for the SDSS catalog. With the exception of an anomaly at a look-back time of 2 Gyr, which we attribute to the difficulty of determining star formation rates at this time; Mathis et al. 2006), the results show clear signatures that the fraction of lost cold baryons increases with time for all but the highest mass galaxies and that the fraction of lost gas is heavily dependent on the stellar mass of the galaxy. The lost fraction varies between about 10% and 20% for M_\star > 10^{12} M_\odot and ~80% and 90% for low-mass (M_\star \leq 10^9 M_\odot) galaxies. The significant loss of gas from the low-mass systems is not surprising, given the small potential wells involved, and may be responsible for the lack of observed low-mass galaxy satellites compared with simulations (Klypin et al. 1999, Moore et al. 1999), even including the latest dwarfs detected in SDSS (e.g., Belokurov et al. 2007). Our results agree with chemical evolution models for elliptical galaxies (Matteucci
and could be explained by an inverse-wind scenario for galaxy evolution, i.e., that the most massive systems are the first ones to undergo mass loss via galactic winds. In any event, our results show clearly the downsizing character of the galaxy population, with the star formation in high-mass galaxies essentially complete at early times.

We wish to thank Simone Recchi, Sheila Kannappan, Daniela Calzetti, and Antonio Pipino for many interesting discussions. F. C. thanks the hospitality of the Department of Physics and Astronomy of the University of Pennsylvania, where part of this work was carried out. We thank an anonymous referee for comments and suggestion that helped us improve the paper.

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