The role of gas infall in the evolution of disc galaxies

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ABSTRACT
Spiral galaxies are thought to acquire their gas through a protracted infall phase resulting in the inside-out growth of their associated discs. For field spirals, this infall occurs in the lower density environments of the cosmic web. The overall infall rate, as well as the galactocentric radius at which this infall is incorporated into the star-forming disc, plays a pivotal role in shaping the characteristics observed today. Indeed, characterising the functional form of this spatio-temporal infall in-situ is exceedingly difficult, and one is forced to constrain these forms using the present day state of galaxies with model or simulation predictions. We present the infall rates used as input to a grid of chemical evolution models spanning the mass spectrum of discs observed today. We provide a systematic comparison with alternate analytical infall schemes in the literature, including a first comparison with cosmological simulations. Identifying the degeneracies associated with the adopted infall rate prescriptions in galaxy models is an important step in the development of a consistent picture of disc galaxy formation and evolution.

Key words: galaxies: formation – galaxies: discs – galaxies: gas

1 INTRODUCTION
Numerical chemical evolution models (CEMs) are one of the most flexible (and long-standing) tools for interpreting the distribution of metals in both the gas and stellar phases of galaxies. The power of CEMs lies in the rapid and efficient coupling of star formation and feedback prescriptions, with the stellar nucleosynthesis, initial mass function formalisms, and treatments of gas infall/outflow. While lacking a self-consistent (hydro-)dynamical treatment, the ability to explore these parameter spaces on computing timescales of minutes rather than months, ensures CEMs maintain a prominent role in astrophysics today.

The initial motivation for the development of CEMs was the identification of what is now known as the G-dwarf Problem (van den Bergh, 1962; Schmidt, 1963; Lynden-Bell, 1975); specifically, there is an apparent paucity of metal-poor stars in the solar neighbourhood, relative to the number predicted to exist should the region behave as a ‘closed-box’, i.e. one in which gas neither enters nor departs. It was recognised that a viable solution to the G-dwarf Problem lay in the relaxation of this closed-box assumption, via the inclusion of a gas inflow prescription (Larson, 1972; Edmunds, 1990). The infall of metal-poor gas can then dilute the existing elemental abundances, whilst simultaneously increasing the early star formation rate, thus producing a stellar metallicity distribution shifted to moderately higher metallicities. Moreover the star formation sustained by metal-poor gas accretion self-regulates to produce a constant gas-phase metallicity close to the stellar yield (i.e., close to the solar metallicity). The G-dwarf problem also appears in external galaxies, as M 31 (Worthey, Dorman, & Jones, 1996). Building on this framework, most classical models of disc formation assume a protogalaxy or dark matter halo which acts as the the source of the infalling gas (Lacey & Fall, 1983, Güsten & Mezger, 1983, Lacey & Fall, 1985, Matteucci & Francois, 1989, Portinari, Chiosi, & Bressan, 1998) without which, in addition, radial abundance gradients are increasingly difficult to recover.

Extensions of this classical framework include those employing a multiphase representation for the interstellar medium

1 Some more recent models include two or even three infall phases, each corresponding in turn to the formation of the halo, followed by that of the thick and thin discs (Chiappini, Matteucci, & Romano, 2001; Chiappini, Matteucci, & Meynet, 2003; Fenner & Gibson, 2006; Micali, Matteucci, & Romano, 2013).
the star formation rate (SFR), since it is roughly one order of
fall rate; such a value poses a problem when it compared with
cold gas, neglecting the likely more dominant background reser-
Sancisi et al. (2008) value is, however, calculated using only the
Similarly, it has been suggested that the high N2
the typical accretion rate would be
the most prominent example is NGC 5253,
In fact, it seems be rotating slower than in discs and moving slowly toward inwards
and moving slowly toward inwards (Oosterloo 2004). However, most of ob-
the HVC’s are the building blocks of galaxies, and situated
within the halo at galactocentric distances less than ~40 kpc, con-
sistent with the predictions of cosmological hydrodynamical simu-
lations (Connors et al. 2006). These clouds are comprised of low-
metallicity gas (e.g. Gibson et al. 2001), consistent with the ma-
material being the fuel out of which the disc forms. It should also be
noted that there now exists recent observations which suggest the
infall of low-metallicity H1 gas in dwarf galaxies triggering
star formation therein. The most prominent example is NGC 5253,
but additional examples are described by López-Sánchez et al. (2010);
Oosterloo (2004) estimated that, if bumps of H1 gas have
a total mass of order 10^9 M⊙ and are accreted in 10^9 yr, the
The consequence is that there remain only select examples in
the literature which reproduce successfully and simultaneously
both in terms of size and relative proportions) the characteristics
of late-type discs and their spheroids (e.g. Brook et al. 2012;
Vogelsberger et al. 2013; Schaye et al. 2015). Bearing in mind this
cautions statement, it is interesting to note that these simulations suggest that most of the baryons in galaxies are accreted diffusely,
with roughly 3/4 due to smooth accretion, and 1/4 from mergers.
Recently, Brook et al. (2014) have generated a suite of cos-
ological simulations which reproduce the gross characteristics of the Local Group. Analysing these simulations, they find the relationship between the stellar mass and the halo mass (their
Fig. 2 and Eq. 2), valid for a stellar mass range [10^7 − 10^11] M⊙. In the last decade, several techniques have been developed to obtain such a relation between the dynamical mass in the proto-halos and the baryonic mass in the discs, although usually this last one is associated to the stellar mass. One of these statistical approaches connecting the CDM halos with their galaxies is the sub-halo abundance matching technique. With that, the total stellar to halo mass relation (SHMR) is obtained (Shankar et al. 2006, Guo et al. 2010, Behroozi, Conroy, & Wechsler 2010; Behroozi, Wechsler & Conroy 2013; Rodríguez-Puebla, Drory & Avila-Reese 2012; Rodríguez-Puebla et al. 2015). Other formalisms use the halo occupation distribution (HOD), which specifies the probability that a halo of mass M has a given number of galaxies with a certain mass M (or luminosity, colour or type). As a result, the
SHMR is also estimated (Moster et al. 2010; Leauthaud et al. 2010; Yang et al. 2012). A summary of these results can be found in Fig. 5 of (Behroozi, Wechsler, & Conroy 2013). This relation constrains the possible accretion of gas from the halo to the discs.
One of the questions that arises when cosmological simu-
lations and data are compared is, such as Kormendy & Freeman
(2016) states, that there is a collision between the cuspy central density seen in cosmological simulations and the observational
evidence that galaxies have flat cores. This tension there exists from
some years ago and it is still present. The use of a Navarro, Frank & White (NFW) profile, with its ρ ∝ r−1 producing cusps at small
2 Similarly, it has been suggested that the high N/O ratio found in some of these galaxies might be also related to infall of metal-poor gas. See the excellent review by Sánchez Almeida et al. (2014) for details.

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Gas infall and the evolution of disc galaxies

2 MODEL FRAMEWORK

For our calculations we use the SAL07 equations, the details for which are outlined in that work. These authors combine kinematic data of the inner regions of galaxies with global observational properties to obtain the URC of disc galaxies and the corresponding mass distributions. For that they use a universal halo density profile following [Burkert (1995)], while the disc is described by the classical Freeman surface density law. With both components, they compute the two rotation curves that contribute to the total. Using data from rotation curves for around 1000 disc galaxies, and fitting them to the above described theoretical rotation curve, they estimated the URC and correlations between the observational properties and the parameters defining those RCs. These are the expressions given and used here. The SAL07 work is the continuation of that of Persic, Salucci, & Stel (1996), with the difference being that now the results are given directly as functions of $M_{\text{vir}}$, instead of any other observational quantity.

We start by assuming an initial mass of gas in a spherical region or protogalaxy. The total dynamical masses for our theoretical galaxies are taken in the range $M_{\text{vir}} \approx [5 \times 10^{10} - 10^{13}] M_\odot$, with values starting at log $M_{\text{vir}} = 10.75$, increasing in mass in steps of $0.15$, resulting in a total set of 16 models.

For each $M_{\text{vir}}$, the virial radius, $R_{\text{vir}}$, is computed. The latter is defined as being the radius corresponding to the transition between the virialised matter of a given halo and that of the infalling material; formally, this corresponds to:

$R_{\text{vir}} = 259 (M_{\text{vir}}/10^{12} M_\odot)^{1/3} \text{kpc}$

To link the virial mass with the baryonic mass in the disc, $M_D$, the relationship from Shankar et al. (2006, hereinafter SHAN06) is used:

$M_{\text{vir}} [M_\odot] = 2.3 \times 10^{10} \left(\frac{M_{\text{vir}}/3.10^{11} M_\odot}{1 + (M_{\text{vir}}/3.10^{11} M_\odot)^{2/3}}\right)^{3/4}$

In order to obtain the final baryonic disc mass, $M_D$, it is necessary to include the mass tied up in the gas phase. From SHAN06, the atomic gas mass is related with the $B$-band luminosity and therefore with the stellar mass, as:

$M_{\text{gas}} = 2.42 + 0.675 \log M_{\text{vir}}$

through these relationships, we compute $M_D = M_{\text{vir}} + 1.34 \times M_{\text{HII}}$.

Both the virial and disc masses possess an intrinsic radial distribution, and therefore, following again SAL07, we use the rotation curves to compute their respective radial dependencies, as:

$V^2(R) = V_{\text{HI}}^2(R) + V_0^2(R)$

$V_{\text{HI}}(R) [\text{km s}^{-1}] = 6.4G \rho_0 R_0^3 R \left(\ln \left(1 + \frac{R}{R_0} \right) - \frac{R}{R_0} - \frac{1}{2} \ln \left(1 + \frac{R^2}{R_0^2} \right) \right)$.

where $\rho_0$ is the central density of the halo:

$\log \rho_0 [\text{g cm}^{-3}] = -23.773 - 0.547 \log \left(\frac{M_{\text{vir}}}{10^{12} M_\odot}\right)$

and $R_0$ is the core radius for the Burkert profile, taken from Yegorova et al. (2012) (where Eq. 10 from SAL07 was updated), and given by:

$\log R_0 [\text{kpc}] = 0.71 + 0.547 \log \left(\frac{M_{\text{vir}}}{10^{12} M_\odot}\right)$

and

$V_0^2(R) [\text{km s}^{-1}] = \frac{1}{2} \frac{GM_D}{R_0} (3.2x)^2 (I_0 K_0 - I_1 K_1)$.
where \( x = R/R_{\text{opt}} \), the optical radius is defined as: \( R_{\text{opt}} = 3.2R_D \); and \( I_0 \) and \( K_0 \) are the modified Bessel functions computed at 1.6\( R_D \).

The scale-length of the disc, \( R_D \), is given by the expression:
\[
\log R_D [\text{kpc}] = 0.633 + 0.379 \log \left( \frac{M_D}{10^{11} M_\odot} \right) + 0.069 \left( \log \left( \frac{M_D}{10^{11} M_\odot} \right)^2 \right) \tag{7}
\]

We define a characteristic radius for each model as \( R_c = R_{\text{opt}}/2 \). This radius, as \( R_{\text{opt}} \) and \( R_D \), are, however, used only for normalization purposes, and for this work are not related to the surface brightness profile.

Having computed the components of rotation velocity, the radial mass distributions within the halo and disc components, for each value of \( M_{\text{vir}} \), are given by:
\[
M_{\text{hal}}(< R) = 2.32 \times 10^5 R V_{\text{hal}}(R)^2 \tag{8}
\]
\[
M_{\text{dis}}(< R) = 2.32 \times 10^5 R V_{\text{dis}}(R)^2 \tag{9}
\]

To these two components we add a bulge component. To compute this term, we use the fact that correlations between disc and bulge structural parameters exist (Balcells, Graham, & Peletier, 2007; Ganda et al., 2009). From these correlations, we obtain the following expressions for the central velocity dispersion, \( \sigma_0 \), and the effective radius of the bulge, \( R_e \):
\[
\sigma_0 [\text{m s}^{-1}] = 105 R_D^{0.5} \tag{10}
\]
\[
R_e [\text{kpc}] = 0.32 R_D - 0.045 \tag{11}
\]

Then:
\[
M_{\text{bulg}}[M_\odot] = 2.32 \times 10^5 \sigma_0^2 R_e, \tag{12}
\]
and
\[
M_{\text{bul}}(R)[M_\odot] = 2.32 \times 10^5 \left[ \sigma_0 e^{-R/R_e} \right]^2 R. \tag{13}
\]

In the central region \((R = 0)\), we have also added the mass corresponding to the supermassive black hole, \( M_{\text{bh}} \), following the classical expression: \( \log M_{\text{bh}} = \beta \log(\sigma/220) + \alpha \), with \( \alpha = 8 \) and \( \beta = 4 \) (Chang et al., 2013).

Finally, we then have:
\[
M_{\text{tot}}(R) = M_{\text{dis}}(R) + M_{\text{hal}}(R) + M_{\text{bul}}(R). \tag{14}
\]

The 16 calculated models would produce discs with baryonic masses \( M_D \) in the range \( [2.3 \times 10^8 \text{–} 5.5 \times 10^{11}] M_\odot \). The observed galactic masses for which SAL07 estimated the relations used here, lie between \( 10^8 \) and \( 2 \times 10^{11} M_\odot \). Therefore, the first two models have lower masses (2.3 and \( 5.6 \times 10^8 M_\odot \), respectively) outside this range. On the massive end of the spectrum, we have \( \sim \)3 models with masses above this limit, which could therefore be considered more appropriately as spheroids or lenticulars. As such, some caution should be applied when considering the mass extrema of our models.

Table 1 summarises the characteristics of the radial mass distributions, obtained from the above expressions, that define our theoretical protogalaxies. For each model with number \( N \) (column 1), we give the logarithm of the virial mass, which is used to name each model, and the value of this mass, \( M_{\text{vir}} \) in columns 2 and 3; the mass the disc would have at the end of the evolution, \( M_D \), is listed in in column 4; the mass of the bulge, \( M_{\text{bul}} \); in column 5; the virial radius, \( R_{\text{vir}} \); in column 6; the disc scale length, \( R_D \); the optical radius, \( R_{\text{opt}} \); and the characteristic radius, \( R_c \), are in columns 7 to 9. The value of the collapse timescale at the characteristic radius, \( \tau_c \), (see next subsection) is in column 10; the maximum rotation velocity of the disc for each model, \( V_{\text{rot}} \); in column 11; the velocity dispersion, \( \sigma_0 \); at the center of the bulge in column 12; and the effective radius of the bulge, \( R_e \); in column 13.

The total mass radial distributions \( M(R) \) are represented in Fig. 1 (for selected values of \( M_{\text{vir}} \) labelled with their logarithm values in panel a). In panel b) we show the mass included in each radial region, which would be a cylindrical region above and below the corresponding annulus in the disc or equatorial plane in which the gas will fall; that is, \( \Delta M_{\text{tot}}(R) = M_{\text{tot}}(< R) - M_{\text{tot}}(< R - 1) \).

3 INFALL RATES

3.1 The infall rate radial distributions: prescriptions for the collapse timescale

We assume that the total mass is initially in a spherical region in the gas phase, from which it ‘falls’ from the halo onto the equatorial plane. As a consequence of this infall, the disc is formed at the center of the bulge in column 12; and the effective radius of the bulge, \( R_e \); in column 13.

We have already calculated the initial or total mass in the halo, \( M_{\text{hal}} \), (see Fig. 1), in each radial region, and we also know what the corresponding \( \Delta M_{\text{hal}}(R) \) must be. We may, therefore, calculate the collapse time for each radial region as:
\[
\tau(R) = \frac{13.2}{\ln \left( 1 - \frac{\Delta M_{\text{hal}}(R)}{M_{\text{vir}}} \right)} \text{[Gyr]} \tag{15}
\]

With the knowledge that the collapse timescale depends on the dynamics of the gas, and that spiral discs possess clear radial density profiles, it should not be surprising to realise that \( \tau \) will have a radial dependence. Some others have already included this radial
Table 1. Characteristics of the theoretical galaxies modeled in this work.

| N | Name | $M_{\text{vir}}$ [$10^{10}$ $M_{\odot}$] | $M_{\text{D}}$ [$10^{11}$ $M_{\odot}$] | $M_{\text{bulge}}$ [$10^{10}$ $M_{\odot}$] | $r_{\text{vir}}$ [kpc] | $\tau_{\text{D}}$ [Gyr] | $\tau_{\text{opt}}$ [Gyr] | $r_{\text{c}}$ [kpc] | $V_{\text{opt}}$ [km s$^{-1}$] | $\sigma_{\text{opt}}$ [km s$^{-1}$] | $r_{\text{e}}$ [kpc] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 10.75 | 5.62 | 0.023 | 0.0084 | 99.328 | 4.291 | 4.154 | 2.071 | 106.769 | 43.668 | 122.046 | 0.382 |
| 2 | 10.90 | 7.94 | 0.056 | 0.070 | 111.335 | 1.347 | 4.312 | 2.156 | 48.801 | 47.231 | 124.703 | 0.398 |
| 3 | 11.05 | 11.22 | 0.14 | 0.087 | 124.920 | 1.469 | 4.701 | 2.351 | 25.758 | 55.764 | 131.078 | 0.438 |
| 4 | 11.20 | 15.85 | 0.33 | 0.122 | 140.163 | 1.674 | 5.357 | 2.679 | 16.057 | 70.210 | 141.338 | 0.506 |
| 5 | 11.35 | 22.39 | 0.75 | 0.184 | 157.265 | 1.967 | 6.295 | 3.148 | 11.982 | 89.870 | 155.119 | 0.602 |
| 6 | 11.50 | 31.62 | 1.51 | 0.288 | 176.455 | 2.334 | 7.470 | 3.735 | 9.901 | 112.342 | 171.199 | 0.723 |
| 7 | 11.65 | 44.67 | 2.67 | 0.454 | 197.985 | 2.744 | 8.781 | 4.390 | 8.773 | 134.799 | 187.931 | 0.858 |
| 8 | 11.80 | 63.10 | 4.24 | 0.680 | 222.143 | 3.172 | 10.150 | 5.075 | 8.054 | 155.754 | 204.317 | 0.999 |
| 9 | 11.95 | 89.13 | 6.25 | 1.014 | 249.249 | 3.618 | 11.577 | 5.788 | 7.549 | 175.306 | 220.413 | 1.145 |
| 10 | 12.10 | 125.9 | 8.82 | 1.495 | 279.662 | 4.098 | 13.114 | 6.557 | 7.558 | 194.300 | 236.844 | 1.303 |
| 11 | 12.25 | 177.8 | 12.19 | 2.192 | 313.786 | 4.636 | 14.835 | 7.417 | 6.843 | 213.516 | 254.300 | 1.480 |
| 12 | 12.40 | 251.2 | 16.67 | 3.340 | 352.073 | 5.255 | 16.815 | 8.408 | 8.586 | 237.362 | 273.360 | 1.664 |
| 13 | 12.55 | 354.8 | 22.70 | 5.250 | 395.033 | 6.837 | 21.880 | 10.940 | 6.213 | 254.425 | 294.508 | 1.922 |
| 14 | 12.70 | 501.2 | 30.84 | 8.579 | 443.234 | 8.317 | 24.541 | 12.225 | 6.110 | 295.146 | 339.232 | 2.469 |
| 15 | 12.85 | 660.7 | 39.40 | 13.18 | 485.996 | 9.087 | 29.079 | 14.539 | 5.999 | 324.533 | 374.896 | 2.945 |

Figure 2. a) Dependence of the collapse timescale $\tau$ with galactocentric radius $R$. Each solid line represents a given radial mass distribution for a given $M_{\text{vir}}$, represented with the same colours as in Fig. 1. The long dashed lines represent the radial distributions of the collapse timescales for similar models from the MD05 grid. b) Comparison of the radial dependence of the collapse time scale of the most similar models with the radial dependence for the infall rate in their models (Lacey & Fall, 1985; Matteucci & Francois, 1989; Portinari, Chiosi, & Bressan, 1998; Boissier & Prantzos, 2000; Renda et al., 2005; Fenner & Gibson, 2006), by assuming different expressions. In fact, such a radial dependence is inherent to classical ‘inside-out’ disc formation scenarios, and is essential for obtaining the observed density profiles and radial abundance gradients. Since the mass density seems to be an exponential, we have also assumed an exponential expression for the collapse timescale in MD05, with a steep dependence with galactocentric radius; conversely, other chemical evolution models employed more conservative linear dependencies on galaxy radius.

The resulting radial distribution of $\tau(R)$ for this new grid is shown in Fig. 2. In panel a), these values are shown, in logarithmic scale, for the same models as in Fig. 1 represented with the same colours and line coding. Solid lines are the results of this work, while long-dashed lines are the collapse time-scale used in MD05, for the closest model in rotation velocity. Functionally, the new (non-linear) collapse timescales are very different from the older models (upper panel). The most central regions (<2 kpc) show a linear behaviour, linking the bulge with the more ‘curved’ expression corresponding to the disc. One can see that the inner regions now have now longer timescales compared with the MD05 prescriptions, while in the outer discs, the values are more comparable (although typically slightly shorter when compared with the older models).

In the panel b) we show the curve corresponding to the MWG-like model, (N = 9) for this work, compared with our previous MD05 model for the MWG (model ND5=28) and other (all linear) forms drawn from the literature (and labelled accordingly). One can see that the red line (our model, here) shows longer collapse timescales at a given radius than the other models, except for the inner disc of the Renda et al. (2005) model (although the difference between these two is minimal at these galactocentric radii).

As a consequence of this varying collapse timescale with radius, a different infall rate is produced in each radial region, building the disc in an inside-out fashion over a Hubble time. In Fig. 3 we show the evolution with redshift of the predicted infall rate, $dM_{\text{D}}/dt$, for regions located at different galactocentric radii in: a) a low mass galaxy, b) a galaxy representing the MWG, and c) a massive galaxy. We see that the very central regions – purple in a) or purple and blue lines in b) and c) – where the bulge is located, show a strong variable infall rate compared with the disc regions, where the curves are essentially flat until $z = 2$, and then slightly decreasing to $z = 0$. The black lines for $R = 7, 16, 28$ kpc are below the observational data. This is interesting, mainly if we take into account that the optical radius in MWG is $\sim 13 - 14$ kpc; that is, the infall rate seems to define well the size of the disc. An additional characteristic highlighted by this figure is that even with different absolute values, the infall rate behavior is very similar in
Figure 3. The infall rate in logarithmic scale as a function of the redshift $z$ for several radial regions, as labelled, in: a) a low-mass galaxy ($\log M_{\text{vir}} = 11.05$); b) a MWG-type galaxy ($\log M_{\text{vir}} = 11.95$); and c) a massive galaxy ($\log M_{\text{vir}} = 12.55$). The red point with error bars is the observational estimate for the MWG (Sancisi et al. 2008).

Figure 4. The time evolution of the infall rate density as (dM/dt dS) in $M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ units, for three different radial regions, as labelled, compared with results from Courty et al. (2010) for galactocentric radii 4.5, 8.5, and 12.5 kpc, as open dots, filled dots, and stars, respectively. The dashed line are similar radial region results drawn from the chemical evolution model of Chiappini, Matteucci, & Gratton (1997).

The comparison of the detailed infall rates from our models with cosmological simulations is not straightforward; the public availability of simulation suites such as Illustris (Nelson et al., 2015b) will aid in the future, but even that amazing data-set has spatial resolution limitations which makes tracing sub-100 pc disk ‘impact’ positions for infalling gas very difficult. And being a moving mesh, rather than particle-based, tracing the temporal history of said infalling gas is non-trivial. We have undertaken a cursory initial comparison though with the cosmological mesh simulation of Courty et al. (2010), as a demonstrator for what will be a more ambitious comparison in the future. For this particular simulation, the authors use multi-resolved, large-scale structure, N-body/hydrodynamical simulations, whose initial conditions are re-centered on a Milky Way sized halo with $M_{\odot} = 7.2 \times 10^{11} M_\odot$. The simulations include, in addition to gravitation and gas dynamics, star formation and its associated thermal and kinetic feedback from supernovae. They identified a large reservoir of gas in the halo fueling the disk within the virial radius, and quantified the gas accretion rate by computing the gas flowing through spherical surfaces or slabs located at different galactocentric distances (or distances above the mid-plane, in the case of slabs). In Fig. 4 we have represented our infall rates fluxes (that is, as infall rate surface densities), corresponding to $\log M_{\text{vir}} = 11.95$ ($M_{\text{vir}} = 8 \times 10^{11} M_\odot$), as a function of time, for three radial regions located at inner, -solar, and outer regions, plotted with different colours, as labelled.

We have included here the results from Courty et al. (2010), (their Fig.3, right panel), estimated (only account for the hot gas) for three galactocentric radii of 4.5, 8.5, and 12.5 kpc, shown by open dots, filled dots, and stars, respectively, and also the results for Chiappini, Matteucci, & Gratton (1997), drawn as dashed lines for similar radial regions. We see that our results reproduce the same behavior found by cosmological simulations: a clear evolution of the infall rates decreasing with time, and also with radius at a given time. This is expected for an inside-out formation process for the galactic disk.
3.2 The dependence on the dynamical mass: the halo-disc ratio

We defined in Section 2, a characteristic radius, $R_c$, that we use in comparing radial mass distributions of different sizes. We have calculated the collapse timescale for this particular radius, interpolating in the radial distributions of $\tau(R)$, thus finding the characteristic collapse timescale, $\tau_c$, which is in column 10 of Table 1, for each galaxy.

We plot in Fig. 5 this $\tau_c$ as a function of the maximum rotation velocity of the disc. The results of our work here (red) are compared with those employed in MD05 (blue), computed, as said, by the expression from Gallagher, Hunter, & Tutukov (1984). Although a similar dependence on the total mass still appears, with shorter $\tau_c$ for massive galaxies and longer times for the low-mass galaxies, differences among both grids appear in both ends of the maximum rotation velocity range. For massive galaxies (essentially more massive than MWG), $\tau_c$ is now longer than in the older MD05 models, while it is shorter for the lower-mass galaxies.

We now integrate the infall across all radial zones to derive the infall rate for the whole disc for each galaxy. This way we may compare the total infall rate for different virial mass galaxies. Such as we see in Fig. 6 where this total infall rate for the same examples of Fig. 1 are represented as solid lines, the gas falls from the halo to the disc with a different rate depending on the total mass, as expected from Fig. 5. In panel a) we compare these with the models from MD05 (short-dashed lines), where it is clear that the infall rate now is more constant in time and, therefore, maintains higher values (than previously) for the more massive galaxies, at the present time.

Panel b) of Fig. 6 compares our results with the cosmological simulations presented by Dekel, Sari, & Ceverino (2009) and Faucher-Giguère, Kereš, & Ma (2011). Both sets of simulations are clearly more variable in time, in better agreement with our old models, but with higher absolute values. It is necessary though to note that these particular simulations lead to primarily massive spheroidal systems (rather than late-type discs). The cosmological simulations from Illustris (Nelson et al. 2015a) produce discs more similar to those observed in nature. In Nelson et al. (2015b), the team analyse how galaxies acquire their gas in simulations, with and without feedback. They found that the time taken for the gas to cross the virial radius increases by a factor of $\sim 2-3$ in the presence of feedback, but is independent of the halo mass (being in the range $10^{10}$ to $10^{12} M_\odot$), as we also found. Using their Fig. 8, we plot in Fig. 6 the redshift evolution of the non-feedback simulation. We see that these results show a much lower infall rate than the old spherical galaxy simulations, and more in agreement with our (slightly) flatter models. It is necessary to be clear, however, that this line corresponds to the accretion corresponding to a virial mass $M_{\text{vir}}=11.30$; that is, it may be compared with our cyan line, which lies below. It implies that this model will create a more massive disc than ours’ for the same virial mass. We have also shown the standard value of the infall rate obtained for the HVCs in the MWG (San
c
ei et al. 2008). This value, which reproduces well the infall prediction for the solar region, is, however, lower than expected when the total infall for the closest-to-MWG simulated galaxy (red or green line) is considered. In that case, the value of Lerner & Howk (2011) is, however, well reproduced. The value at $z = 0.375$ is an estimate obtained from the recent work by Fernández et al. (2016) who detect HI at the highest redshift, to date. They give the masses for the diffuse (and molecular gas), and use the stellar mass from Spitzer IRAC data: $M(\text{H}_2)=2\times10^{10} M_\odot$, the molecular one is $M(\text{H}_2)=1.8-9.9\times10^9$ Msun, and the stellar mass $M_* = 8.7 \times 10^{10} M_\odot$. Using these numbers, a total disc mass is estimated in the range $[3.4-21.5] \times 10^{10} M_\odot$. If the disc accreted this mass in $\sim 8$ Gyr (the evolutionary time from $z \sim 7$ to today), the averaged value for the infall rate would be $\sim 17-27 M_\odot \text{yr}^{-1}$. Taking into account that this is an averaged value across the full redshift range, and that the infall rate probably was greater at higher redshift, we reduce the value by a factor of two, that is $\log(dM/dt) = 1.00$. We note that taking into account the total mass of the disc, this galaxy would lie between our models 11 and 13, corresponding to $\log M_{\text{vir}} = 12.25$ and 12.55 (represented by magenta and orange lines in the accompanying figure). We see that these recent observational data compares very well with our model predictions.

The infall rate behaviour is very similar for all galaxy masses, with differences mainly in the absolute value. As such, we have normalised the infall rate to the final mass of the disc, $M_f$ and show the results in Fig. 7. In a) we normalise to the final disc mass $M_f$ while in panel b) we normalise to the disc mass at each time $M(t)$. We see that in panel a) all infall rates coincide to the same value $dM_f^*/M_f \sim 0.1 \text{ Gyr}^{-1}$, at $z \sim 1.3$, while in panel b) it is clear that the last normalised infall rate is practically the same for $z > 2.5$. This means that at high redshift, discs grow in the same proportion for all virial masses and it is only recently that differences appear.

The infall rate at the present time shows a correlation with the virial mass of the dark halo or with the mass in the disc $M_D$, as we show in Fig. 8. In panel a), we see that the infall rate depends on the mass, increasing with $M_D$. However, in panel b), where the normalised infall rate is represented, the contrary occurs: low mass galaxies are now suffering a higher infall rate in proportion to the total mass of their discs, while the massive discs have now a very low rate (almost an order of magnitude lower). This is again in agreement with the scenario where low mass galaxies form their discs well after the most massive ones (the latter of which create their discs rapidly).

3.3 The growth of spiral discs

As a consequence of this gas infall scenario, the disc is formed in an inside-out fashion. The proportion of the final mass in the disc
Figure 6. The infall rate as a function of the redshift $z$ for galaxies of several virial mass, with the same coding as Fig. 1. a): comparison with MD05 infall rates shown by short-dashed lines. b): comparison with cosmological simulations, as long-dashed lines, from Dekel, Sari, & Ceverino (2009, DEK09) and Faucher-Giguère, Keres, & Ma (2011, FG11), and as short-dashed line from Nelson et al. (2015, NEL15), as labelled. The solid red pentagon is the estimated value from Sancisi et al. (2008) while the blue triangle is given by Lehner & Howk (2011). The green square is obtained from Fernández et al. (2016) for the highest redshift galaxy observed in HI.

Figure 7. The infall rate normalised to a) the final mass of the disc $\frac{\log dM}{dt}$ and b) to the disc mass at each time $M_D(t)$, both in logarithmic scale, as a function of the redshift $z$ for the same galaxies as shown in Fig. 6.

Figure 8. a) The infall rate at the present time ($z = 0$), $(\frac{\log dM}{dt})_P$ and b) as normalised to the final mass of the disc at the present time $(\frac{\log dM}{dt})_P/M_D$ as a function of disc mass $M_D$.

Figure 9. a) The virial to the disc mass, $M_v/M_D$, resulting from the applied collapse timescale prescriptions of our new grid (red points), compared with our previous results from Mollá & Díaz (2005) (blue points). We also show the relationship from Mated (1998, hereinafter BRO14), both obtained for galaxies of the Local Group. Our older results from MD95 had a similar slope to the one from Mated (1998), but the absolute value given by the latter is somewhat smaller, which is due to the $M_* / L$-ratio employed to transform the observations (luminosities) to stellar masses. The cosmological simulations begin to be able to predict discs of the appropriate size. We have drawn in the same Fig. 9 the results obtained by Doménech-Moral et al. (2013, hereinafter DOM12) and by Brook et al. (2012, hereinafter BRO12). We also plot the results obtained by Leauthaud et al. (2010, hereinafter LEAU), who studied the stellar-to-halo mass relation using COSMOS data, for the lowest redshift they give (as labelled in the figure). Our new models are calculated to predict the line from SHAN06 and are close to the one from LEAU, and, in excellent agreement with DOM12, BRO12, and BRO14. In the cases of LEAU and SHAN06, lines show an increase for high disc masses which, obviously, is not apparent in our old models, since we had assumed a continuous dependence of the collapse time scale with the dynamical mass. This increase is, however, rather modest for the SHAN06 line and the models follow this trend. In panel b) of the same figure we show our results for redshifts $z = 0, 1, 2$, and $4$, with different colours, as labelled. The relation looks similar for $z \leq 2$, however, when we see the track for a particular galaxy, shown by black lines for three values of $\log M_{vir} = 10.75, 11.95, and 13.00$, the evolution is clear, with decreasing ratios $M_{vir}/M_D$ for increasing $M_D$. Results for $z = 1$ are close to the LEAU data for the range $0.7 < z < 1.0$.
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Figure 9. a) The ratio $\frac{M_{\text{var}}}{M_D}$ at $z = 0$ as a function of the mass in the disc $M_D$. Our models, calculated to follow the SHAN06 prescription (black line), are the red dots, while the blue dots are the MD05 results. The magenta, cyan, and black lines are the prescriptions obtained by Mateo (1998), labelled as MAT98, and from BRO14 and SHAN06 from observations of the Local Group of galaxies for the first two, and from halo distribution data, for the latter. The orange line shows results from LEAU for COSMOS data for the lowest redshift range. Cosmological simulations are drawn with purple squares and green stars from DOM12 and BRO12, respectively; b) Our results for the ratio $\frac{M_{\text{var}}}{M_D}$ at $z = 0$, 1, 2, and 4, represented with different colours, as labelled, as a function of the mass in the disc $M_D$ at each time, compared with results from LEAU for $z \sim 0.7 - 1.0$ (orange dashed line). Black lines join the evolutionary tracks for individual galaxies with $\log M_{\text{vir}} = 10.75, 11.95$, and 13.00.

Figure 10 shows the evolution of the half (baryonic) mass radius of the disc, $HMR$, with redshift, for the same galaxies of Fig. 1. This figure also supports the notion that the growth of massive discs is more rapid than the growth of the low mass ones (which are still forming their discs). In panel a) we see directly the redshift evolution of these HMRs. Clearly, the lowest mass galaxies evolve very late compared with the others. This difference of behaviour is even clearer in panel b), where the HMRs are normalised to their final value reached at the end of the evolution (or the present time), $HMR_P$. In that case, most of galaxies show a similar evolution, except the lowest mass galaxies, which have very separated evolutionary tracks.

We also check how the discs grow by comparing the fraction of the final disc mass which is in place at each redshift in Fig. 11. Obviously, all tracks end at a value of unity at $z = 0$ (100% of $M_0$ in the present time), but the evolution differs for each galaxy depending on the virial mass. This kind of plot is similar to that obtained by PÉREZ et al. (2013) for the CALIFA survey (Calar Alto Legacy Integral Field Area, SÁNCHEZ et al. 2012) galaxies as shown in panel a), where we represent the proportion of the total mass placed in the disc as a function of the disc age, equal to $13.8 - t$, $t$ being the evolutionary time. In panel b) the same is shown as a function of the redshift $z$.

On the other hand we may also compare the final $HMR_P$ or...
radius at the present time, for different galaxies. Panel a) of Fig. 12 plots HMR$_R$ as a function of the disc mass, $M_D$, also at the present time. Clearly, there is a relationship between the baryonic mass in discs and their sizes, measured by the HMR$_R$, as expected. Actually, by assuming that discs are exponential and using these quantities, we also might calculate the surface density at the center of the galaxy as $\Sigma_0 = M_D / 4\pi R^2$.

4 DISCUSSION

By imposing the final disc mass distributions resemble those from Salucci et al. (2007), we have computed the infall rates in the discs of spiral galaxies. From our models, we have reached important results regarding the mass assembly in disc galaxies compared with previous results in the literature. The new prescriptions adopted in this work resulted in a MWG analogue where radial re-

Fig. 12. a) The present half mass radius $HMR_R$ and b) The present central surface density $\Sigma_0$, as a function of the final mass of disc $M_D$, on a logarithmic scale.

most of the previously available timescales in the literature. In Fig. 3, a clear dependence of the gas infall rate on redshift, and also on radius, appears except for the outer disc regions where the infall rate is almost constant in spite of redshift variations. At the inner disc regions and the bulge, however, the cold gas accretion is higher at high redshifts than now. This cold gas accretion in the inner regions of high-redshift galaxies is supported by observations: Cresci et al. (2010) find that a massive infall of gas in the central regions of high-redshift galaxies ($z \sim 2-3$) is needed to explain the gas metallicity distribution within these galaxies. In the local universe there is also evidence that there still exists cold gas accretion in disc galaxies (e.g. Sánchez Almeida et al., 2014, and references therein).

With our collapse timescales varying with $R$, the resulting discs are also created in agreement with the inside-out formation scenario. Following Fig. 3 the inner regions of a galaxy are formed faster than the outer ones, while these latter present infall rates which are less variable with redshift. In agreement with this, the outer regions of the MWG analogue model are still accreting gas. This new result is in agreement with surveys of extended UV discs around both early- and late-type galaxies in the local universe that suggest gas accretion in their outer parts (Lemonias et al. 2011, Moffett et al., 2012). In fact, these latter authors establish that gas-rich galaxies below a stellar mass of $M_* \sim 5 \times 10^9$ M$_\odot$ display UV-bright discs, supporting an active disc growth. This limit is basically the value in which $r_c > T_{\text{UNIVERSE}}$ in our models, as seen in Table 1, between models 4 and 5. This limit in the collapse timescale also appears when considering the different radial regions within discs, thus suggesting that these discs may continue growing at the present time even in the most massive galaxies.

Another important result that we have obtained is the dependence on redshift of the infall rate normalised to the disc mass in each time-step for different $M_{\text{vir}}$, shown in Fig. 8. The gas accretion profile is similar for all simulated galaxies at $z > 2$, and only for lower redshifts does the infall rate depend on $M_{\text{vir}}$. This has important implications for how discs grow their masses at high redshifts. Since galaxies form and evolve by accreting gas from their surroundings, our models suggest that the accretion of gas is similar for spiral galaxies, regardless of their masses. Kereš et al. (2009) showed that cold mode accretion via filaments is responsible for the supply of gas in galaxies. Kereš & Hernquist (2003) showed that the gas is accreted via filaments from the intergalactic medium and these filaments can condense into clouds and provide gas for star formation. These clouds may be analogs of HVCs surrounding the MWG which are thought to provide the fuel for star formation in the Galaxy. Therefore, the similarity between the accretion rates found here for spiral galaxies with different $M_{\text{vir}}$ suggests an analogous disc growth for these galaxies and, consequently, similar disc properties. We will analyse these properties, as the possible formation of stars in the outer regions of discs or the variations of radial gradients of abundances, in a future work (Mollá et al., in preparation). Therein, we will take into account the star formation processes and the consequent metal enrichment, not included yet here, when the chemical evolution computed is computed self-consistently.

5 CONCLUSIONS

In this work we have presented the infall rates used as input to a grid of chemical models for spiral galaxies. We also performed a systematic comparison with data and competing models in the lit-
erature, including cosmological simulations. Our main conclusions can be summarised as follows:

(i) The more massive the galaxy, the higher the absolute value of the infall rate at all redshifts.

(ii) The infall rates necessary to reproduce the relationship between $M_{\text{vir}}$ and $M_*$ are smoother than the ones assumed in classical chemical evolution models, including our earlier generation of models (MD05). They are also lower and smoother than the accretion rates produced in cosmological simulations which create spheroids and are in better agreement with those resulting in realistic late-type discs (employing contemporary prescriptions for star formation and feedback).

(iii) The evolution of the infall rate with redshift is quite constant for discs, decreasing smoothly for $z < 2$ and showing very similar behaviour for all radial regions, with differences only in the absolute value. This smooth evolution is different than the steep decline with redshift shown for bulges.

(iv) The normalised infall rate is essentially the same for all discs until $z = 2$, and shows only small differences for $z < 2$.

(v) The final relationship among disc and halo masses, denoted as SHMR, obtained by these new prescriptions, agrees well with observations and cosmological simulations.

(vi) From redshift $z = 2.5$ to today, discs grow in size by a factor of two (except for the lowest mass galaxies), while the disc masses increase by a factor of five to ten.

(vii) These infall rates (decreasing with time and with radius within each theoretical galaxy) are in agreement with the classical inside-out scenario, and also with the cosmological simulations infall rates from Courty et al. (2010).

(viii) The growth of discs continue to the present time, with gas accretion across the discs of low mass systems, and in the outer regions of more massive spirals.

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