Disc galaxy evolution along the Hubble sequence

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ABSTRACT

Galaxy discs are characterized by star formation histories that vary systematically along the Hubble sequence. We study global star formation, incorporating supernova feedback, gas accretion and enriched outflows in discs modelled by a multiphase interstellar medium in a fixed gravitational potential. The star formation histories, gas distributions and chemical evolution can be explained in a simple sequence of models which are primarily regulated by the cold gas accretion history.

Key words: stars: formation – supernovae: general – galaxies: formation – galaxies: ISM.

1 INTRODUCTION

The two most striking characteristics that define the Hubble sequence are morphology and star formation activity. The former is best addressed by numerical simulations (Abadi et al. 2003; Robertson et al. 2004; Sharma & Steinmetz 2005; Governato et al. 2007). However, the latter aspects are so complex that most discussions of disc star formation and chemical evolution are based on analytical calculations (Efstathiou 2000; Ferreras & Silk 2001; Silk 2001, 2003; Matteucci et al. 2006; Naab & Ostriker 2006). This paper extends the analytic approach to study star formation histories that vary systematically along the Hubble sequence. We study global star formation, incorporating supernova (SN) feedback, gas accretion and enriched outflows in discs modelled by a multiphase interstellar medium (ISM) in a fixed gravitational potential.

One of the current problems afflicting galaxy formation models is the role of gas infall. For both ellipticals (Bower et al. 2006; Croton et al. 2006) and massive discs at $z \sim 2$ (Forster Schreiber et al. 2006), infall rates are sufficiently high from cold dark matter (CDM) theory (ellipticals and discs) and observations (discs) that infall must be quenched, otherwise distant ellipticals are too blue and the discs are too massive by the current epoch. The problems may be related via feedback from active galactic nuclei (AGN), but the details are poorly understood with regard to the resulting star formation history, gas infall rates and chemical evolution. In this paper, we focus on disc galaxies, and develop a phenomenological description of disc evolution in which the onset and duration of the gas infall history are found to be the controlling parameters. The star formation histories, gas distributions and chemical evolution can be explained in a simple sequence of models which are primarily regulated by the cold gas accretion history.

One of the main features of galaxies that characterizes the significance of the Hubble sequence is the wide range in young stellar content and star formation activity. This variation in stellar content is part of the basis of the Hubble classification itself, and understanding its physical nature and origins is fundamental to understanding galaxy evolution in its broader context. In this paper, we construct a sequence of evolutionary models in which present-day properties of different types of disc galaxies are reproduced.

The first implementation of SN-driven feedback in the context of CDM was to account for the properties of dwarf galaxies (Dekel & Silk 1986), and subsequent studies have explored the role of SN feedback in more massive galaxies. Feedback is an important element in our attempts to model galaxy evolution. Energy injection from SNe is probably the most plausible feedback mechanism for systems with virial temperatures higher than $10^5$ K. Winds from quasars might also disrupt galaxy formation or limit the growth of central black holes. Here, we will be concerned exclusively with SN-driven feedback and we will not consider feedback from an active nucleus. The model presented in this paper is similar to the simple self-regulating model with inflow and outflow developed in Efstathiou (2000), the main difference being in the infall model that we implement. We adopt an exponentially decreasing infall rate normalized in order to reproduce the observed total disc mass density in the solar neighbourhood, whereas in Efstathiou’s model it is the conservation of specific angular momentum that specifies the final radius in the disc for each gas element. Angular momentum conservation is known to be a poor approximation, at least in the numerical simulations, and our more phenomenological model is easily adapted to the chemical evolution constraints.

The main result of this paper is that star formation histories of the different types of disc galaxies can be reproduced using a one parameter model. The key parameter of our model is the time corresponding to the onset of the infall. Using this free parameter, we reproduce the distribution of disc birthrate parameters $b$, the ratio of the current SFR to the average past SFR, for each type of disc galaxy as presented in Kennicutt, Tamblyn & Congdon (1994) and summarized in Fig. 1. We then explore the various implications of the model for the radial and temporal dependencies of the gas fraction, star formation rate (SFR) and metallicity.

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The layout of this paper is as follows. Section 2 briefly reviews the main points of our model and presents some basic results. The model is extended in Section 3 to include an improved treatment of winds and chemical evolution. Finally, in Section 4 we discuss our results and present our conclusions.

2 MODEL

The model described here is a self-regulating model with inflow and outflow. The disc is considered to be a system of independent rings each of 35$r_d$ pc wide (where $r_d$ is in units of kpc). Neither radial inflows nor radial outflows are considered. The ring centred at the galactocentric distance $r_G = 8.5$ kpc is labelled as the solar neighbourhood. For the present-day total disc surface density in the solar neighbourhood, we adopt a value $\Sigma_{tot}(r_G, t_G) = 60 M_\odot$ pc$^{-2}$. (Holmberg & Flynn 2004 found 56 ± 6 $M_\odot$ pc$^{-2}$ for their disc model.)

2.1 Dark halo and disc model

The dark halo is assumed to be described by the Navarro, Frenk & White (1995) profile,

$$\rho(r) = \frac{\delta_0}{(C x)(1 + C x)^2},$$

where $x = r/r_c$, $\rho_0$ is the critical density, $r_c$ is the virial radius at which the halo has mean overdensity of 200 with respect to the background and C is the concentration parameter. For the present model, we adopt a value for $C$ of 10. The circular speed corresponding to this profile is

$$v_H^2(r) = v_*^2 \frac{1}{x} \frac{[\ln(1 + C x) - C x/(1 + C x)]}{[\ln(1 + C) - C/(1 + C)]},$$

where $v_*^2 \equiv \frac{G M_c}{r_c}$, and $M_c$ is the mass of the halo within the virial radius.

For the surface density of the disc at $t = 0$, we assume an exponential profile:

$$\Sigma_{tot}(r, 0) = \Sigma_0 e^{-r/r_d},$$

where $M_D = 2\pi r_d^2 \Sigma_0$, $\Sigma_{tot}(r, 0)$ is the total surface density of the ring centred at galactocentric radius $r$ at $t = 0$, $M_D$ is the total disc mass at $t = 0$ and $r_d$ is the scalelength. In our model the entire gas disc has formed instantaneously at $t = 0$. The rotation curve of a cold exponential disc is given by (Freeman 1970):

$$v_y^2(r) = 2v_*^2 y^2[I_0(y)K_0(y) - 1y/(y)],$$

where $y = r/r_c$ and $v_*^2 \equiv \frac{GM_\odot}{r_c}$. For ratio $v_y^2$ we adopt a value equal to 0.45 that corresponds to the Milky Way. Models using standard disc formation theory with adiabatic contraction in the cusp halo (Klypin, Zhao & Somerville 2002) reproduce the broad range of observational data available for the Milky Way by adopting a viral mass equal to $M_v \approx 10^{12} M_\odot$, baryonic mass equal to $M_{bar} \approx 4 \times 10^{10} M_\odot$ and viral radius $r_v = 258$ kpc. These values in combination with an adopted value for the disc scalelength equal to $r_d = 3$ kpc (Sackett 1997) give $\frac{v_y}{v_*} = 0.45$. In this work, we keep the ratio $\frac{v_y}{v_*} = \text{constant}$ for all the models we present.

The ratio of virial radius of the halo to disc scalelength is defined as the collapse factor $f_{coll} \equiv \frac{r_v}{r_d} = 50$; such a value is needed to reproduce a median value of $\sim 0.05$ for the dimensionless spin parameter of the halo $\lambda_3$ (Efstathiou 2000). The disc is truncated at radius $r/r_d = 7$.

2.1.1 Two-component (stellar and gas) rotating disc

The stellar radial velocity dispersion $\sigma_*$ is related to that of the gas clouds:

$$\sigma_v = a\sigma_g.$$ (5)

Here we assume $a = 5$ (Efstathiou 2000). The scaleheight for a two-component rotating disc is (Talbot & Arnett 1975):

$$H = \frac{\sigma_g^2}{\pi G \Sigma_d [(1 + (\sigma_*/\Sigma_d)/(\sigma_v/\sigma_g))]}$$ (6)

2.2 Epicyclic frequency model

The epicyclic frequency is given by the expression

$$\kappa = 2\omega \left(1 + \frac{r}{2} \frac{d\omega}{dr}\right)^{1/2},$$ (7)

in which $\omega$ is the angular velocity of the disc. In the above equation we replace $\omega = v_{lin}/r$ where $v_{lin} = v_H + v_D$. Thus, the epicyclic frequency (in units of $10^{-15}$ s$^{-1}$) is

$$\kappa = 0.035 \sqrt{2} v_{lin}/r \left(1 + \frac{r}{2} \frac{dv_{lin}}{dr}\right)^{1/2}.$$ (8)

2.3 Star formation rate

In this work we adopt the star formation law proposed in Wang & Silk (1994), to which we refer for a detailed description. The SFR (in units of $M_\odot$ pc$^{-2}$ Gyr$^{-1}$) is given by

$$\psi(r, t) = \frac{\kappa \Sigma_d (1 - Q^2)^{1/2}}{Q},$$ (9)

where $\kappa$ is the epicyclic frequency, $\Sigma_d$ is the gas surface density in units of $M_\odot$ pc$^{-2}$, $Q$ is the gravitational instability parameter.

1 A disc galaxy with scalelength $r_d = 3$ kpc, the width of each zone is equal to $35 \times 3 = 105$ pc.

2 The ratio $v_y/v_*$ defines the disc scalelength $r_d$. The disc scalelength is $r_d = \left(\frac{M_{bar}/4\pi r_d^2}{\rho_{crit}/v_y^2}\right)^{1/3}$ kpc.
creasing function in which the rate of gas infall (in units of M⊙ pc−2 Gyr−1) in each ring is expressed as

\[ f(r, t) = A(r)e^{-t/\tau}, \]

where \( \tau \) (in units of Gyr) is the infall time-scale. The infall rate \( f(r, t) \) is normalized to the present-day local disc density.

The adopted stellar IMF is of the standard Salpeter form:

\[ \frac{dN_\star}{dm} = Bm^{-(1+3\alpha)}, \quad m_l < m < m_u, \quad x = 1.35, \]

where \( m_l = 0.1 \) M⊙, \( m_u = 50 \) M⊙.

For the IMF adopted, one SN is formed for every 125 M⊙ of star formation, assuming that each star of mass greater than 8 M⊙ releases \( 10^{51} E(t_0) \) erg in kinetic energy in an SN explosion. Therefore, the energy injection rate per unit surface area (in units of erg s−1 pc−2) is given by

\[ E_n = 2.5 \times 10^{52} E_{51} \psi_t, \]

where the parameter \( \psi_t \) defines the percentage of SN energy that goes to the ambient medium. For this model we adopt \( \psi_t = 0.03 \).

2.4 Initial mass function (IMF)

The adopted stellar IMF is of the standard Salpeter form:

\[ \frac{dN_\star}{dm} = Bm^{-(1+3\alpha)}, \quad m_l < m < m_u, \quad x = 1.35, \]

(11)

where \( m_l = 0.1 \) M⊙, \( m_u = 50 \) M⊙.

The parameter \( \alpha \) relates the blast wave velocity to the isothermal sound speed through the relation

\[ \gamma = \frac{C_l}{C_s} = \frac{1}{2} \left( \frac{d\log M_\star}{d\log \psi_t} \right) \]

(12)

in units of M⊙ pc−2 yr−1, where \( M_\star \) is the gas surface density in units of 5 M⊙ pc−2, \( \psi_t \) is the cloud radial velocity dispersion in units of 5 km s−1 and \( \gamma = 1.35 \) is the SN rate in units of 10−11 pc−3 yr−1.

The parameter \( \gamma \) relates the blast wave velocity to the isothermal sound speed through the relation

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(13)

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(14)

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(15)

in units of M⊙ pc−2 yr−1, where \( M_\star \) is the gas surface density in units of 5 M⊙ pc−2, \( \psi_t \) is the cloud radial velocity dispersion in units of 5 km s−1 and \( \gamma = 1.35 \) is the SN rate in units of 10−11 pc−3 yr−1.

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(16)

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(17)

in units of M⊙ pc−2 yr−1, where \( M_\star \) is the gas surface density in units of 5 M⊙ pc−2, \( \psi_t \) is the cloud radial velocity dispersion in units of 5 km s−1 and \( \gamma = 1.35 \) is the SN rate in units of 10−11 pc−3 yr−1.

The parameter \( \gamma \) relates the blast wave velocity to the isothermal sound speed through the relation

\[ \gamma = \frac{C_l}{C_s} = \frac{1}{2} \left( \frac{d\log M_\star}{d\log \psi_t} \right) \]

(18)

in units of M⊙ pc−2 yr−1, where \( M_\star \) is the gas surface density in units of 5 M⊙ pc−2, \( \psi_t \) is the cloud radial velocity dispersion in units of 5 km s−1 and \( \gamma = 1.35 \) is the SN rate in units of 10−11 pc−3 yr−1.

The parameter \( \gamma \) relates the blast wave velocity to the isothermal sound speed through the relation

\[ \gamma = \frac{C_l}{C_s} = \frac{1}{2} \left( \frac{d\log M_\star}{d\log \psi_t} \right) \]

(19)

in units of M⊙ pc−2 yr−1, where \( M_\star \) is the gas surface density in units of 5 M⊙ pc−2, \( \psi_t \) is the cloud radial velocity dispersion in units of 5 km s−1 and \( \gamma = 1.35 \) is the SN rate in units of 10−11 pc−3 yr−1.

The parameter \( \gamma \) relates the blast wave velocity to the isothermal sound speed through the relation

\[ \gamma = \frac{C_l}{C_s} = \frac{1}{2} \left( \frac{d\log M_\star}{d\log \psi_t} \right) \]

(20)

in units of M⊙ pc−2 yr−1, where \( M_\star \) is the gas surface density in units of 5 M⊙ pc−2, \( \psi_t \) is the cloud radial velocity dispersion in units of 5 km s−1 and \( \gamma = 1.35 \) is the SN rate in units of 10−11 pc−3 yr−1.

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(21)

in units of M⊙ pc−2 yr−1, where \( M_\star \) is the gas surface density in units of 5 M⊙ pc−2, \( \psi_t \) is the cloud radial velocity dispersion in units of 5 km s−1 and \( \gamma = 1.35 \) is the SN rate in units of 10−11 pc−3 yr−1.
For $10^5 \leq T \leq 10^6$ K we adopt a cooling rate of $\Lambda \approx 2.5 \times 10^{-22} T_s^{1.4}$ erg cm$^3$ s$^{-1}$. Thus, for a gas with primordial composition, the cooling time $t_{cool}$ is

$$t_{cool} = 2\pi T_s^{-1.4} f_{\Sigma}^{0.5}.$$(22)

### 2.8 Outflow model

As mentioned in the previous section, SN bubbles expand, evaporate cold gas and compress the ambient ISM. The compressed ISM will also be driven by a form of wind. In order to study the effects of outflow, we assume a simple phenomenological model for galactic winds where the wind mass-loss rate $M_w$ (in units of $M_\odot$ pc$^{-2}$ Gyr$^{-1}$) is assumed to be proportional to the SFR:

$$M_w = k \psi.$$(23)

We explore many values of $k$ between 0 and 1. The hot gas that escapes from the halo is removed permanently. Superwinds indeed are found around Milky Way type galaxies (Strickland 2007). This is puzzling from the theoretical perspective because SNe are considered to be incapable of driving a strong wind from the gravitational potential well of a massive galaxy. Also, at least one example is known of an extended X-ray halo around a normal massive spiral galaxy (Pedersen et al. 2006). In this case, gravitational accretion and shock heating provides the most plausible source for heating the gas.

### 2.9 Galactic fountain model

Models of gas flow on the galactic scale were first introduced by Shapiro & Field (1976) and subsequently developed by Bregman (1980) and others. The galactic fountain originates from the SNe that warms up the disc gas to temperatures of $10^6$ K. The up-flowing gas cools and condenses into neutral hydrogen clouds that rains on to the disc. The models assume the height to which the hot gas will rise and the expected rate of condensation in the cooling gas depends only on the temperature of the gas at the base of the fountain and the rate of cooling of the up-flowing gas. The rate of cold gas evaporation due to SN explosions is given by equation (17). Instead of assuming that the hot-phase gas returns instantaneously to the cold phase we use the fountain model to define the time $t_{ret}$ after which the hot-phase gas is returned to the cold phase and is available again to make stars:

$$t_{ret} = t_{cool},$$

where $t_{cool}$ is the cooling time given by equation (22). In the model described in this paper after time $t_{ret}$ the hot gas returns to the disc as cold gas at the radius from which it was expelled. Thus, the surface density of the disc at time $t$ and galactocentric radius $r$ is

$$\Sigma_g(r, t) = \Sigma_g(r, t) + \Sigma_{hot}(r, t - t_{ret}).$$

where $\Sigma_{hot}(r, t - t_{ret})$ is the surface density of the hot-phase gas that is produced from SN explosions at time $t - t_{ret}$ and galactocentric radius $r$.

### 2.10 Chemical evolution

We include chemical evolution in the model using the instantaneous recycling approximation. Thus, we assume that all processes involving stellar evolution, nucleosynthesis and recycling take place instantaneously on the time-scale of galactic evolution. The equation of galactic chemical evolution is

$$\Sigma_g \frac{dZ}{dt} = p \psi dt + (Z_F - Z) f dt,$$(26)

where $f$ is the infall rate (in units of $M_\odot$ pc$^{-2}$ Gyr$^{-1}$) and $p$ is the yield (Pagel 1997). We adopt a yield of $p = 0.02$ and assume that the mass accreted to the disc has zero metallicity ($Z_F = 0$). We normalize the metallicities to the solar value for which we adopt $Z_\odot = 0.02$.

### 2.11 Different types of spiral galaxies

To explore the evolution of different types of spiral galaxies we adopt five models in this paper (see Table 1). These models differ only in the mass of the disc and the disc scalelength $r_d$. All the input parameters that these models have in common are summarized in Table 2.

### 2.12 Basic results

In this section we present the basic results of the model discussed in the previous sections. Unless otherwise stated, we adopt a value 0.2 for the parameter $k$ in the outflow model. For clarification of the plots, when results from models Sc and Sd are similar we denote this by a new type of disc galaxy Sc/d. The data for Sc/d type come from the average between the Sc model data set and the Sd model data set.

#### 2.12.1 Distribution of disc birth rate $b$

Values of the birth parameter $b$ were calculated for each type of spiral galaxy. For the calculation of $b$ values we ignore the SFR that corresponds to the first 10$^9$ yr, due to a deficiency in our model. More specifically in the model we assume that the entire gas disc

### Table 1. Five models adopted in this paper.

<table>
<thead>
<tr>
<th>Type</th>
<th>Disc mass $M_D$ ($M_\odot$)</th>
<th>$r_d$ (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>$5.5 \times 10^{10}$</td>
<td>3.00</td>
</tr>
<tr>
<td>Sb</td>
<td>$4.0 \times 10^{10}$</td>
<td>2.70</td>
</tr>
<tr>
<td>Sc</td>
<td>$2.7 \times 10^{10}$</td>
<td>2.37</td>
</tr>
<tr>
<td>Sd</td>
<td>$1.5 \times 10^{10}$</td>
<td>1.95</td>
</tr>
<tr>
<td>Sm</td>
<td>$1.0 \times 10^{10}$</td>
<td>1.70</td>
</tr>
</tbody>
</table>

### Table 2. Input parameters in common for the five models we examine in this paper.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>$r_\odot = 8.5$ kpc</th>
<th>$\Sigma_{tot}(r_\odot, t) = 60$ $M_\odot$ pc$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radius</td>
<td>$r_\odot = 8.5$ kpc</td>
<td>$\Sigma_{tot}(r_\odot, t) = 60$ $M_\odot$ pc$^{-2}$</td>
</tr>
<tr>
<td>Total disc surface density at $r_\odot$</td>
<td>Solar IMF</td>
<td>Solar metallicity</td>
</tr>
<tr>
<td>Star formation IMF</td>
<td>$Z_\odot = 0.02$</td>
<td>$p = 0.02$</td>
</tr>
<tr>
<td>Effective yield</td>
<td>$\epsilon = 0.02$</td>
<td>$\epsilon = 0.02$</td>
</tr>
<tr>
<td>Star formation efficiency</td>
<td>$\epsilon_c = 0.03$</td>
<td></td>
</tr>
<tr>
<td>SN energy transfer parameter</td>
<td>$\tau_f = 0.5$ Gyr</td>
<td></td>
</tr>
<tr>
<td>Infall time-scale</td>
<td>$t_h = 10$ Gyr</td>
<td></td>
</tr>
<tr>
<td>Galactic disc age</td>
<td>$\phi_c = 0.1$</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity effectiveness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar evaporation parameter</td>
<td>$\Sigma^{S}_{\odot} = 95$ pc$^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Disc-to-halo velocity ratio</td>
<td>$\zeta_c = 0.45$</td>
<td></td>
</tr>
<tr>
<td>Collapse factor</td>
<td>$f_{coll} = 50$</td>
<td></td>
</tr>
<tr>
<td>Wind model parameter</td>
<td>$k = 0.2$</td>
<td></td>
</tr>
</tbody>
</table>
**Figure 2.** The disc birthrate parameter $b$, the ratio of current SFR to the average past SFR, plotted against the free parameter $t_{\text{low}}$, for different types of disc galaxies. The dotted line indicates the median value of birthrate parameter, while the dashed lines show the quartiles of birthrate parameter presented by Kennicutt et al. (1994). For clarification of the plot, we define a new type of disc galaxy Sc/d. The data for Sc/d type come from the average between the Sc model data set and the Sd model data set.

has formed instantaneously at $t = 0$: this is unrealistic and leads to very high rates of star formation for the first $10^8$ yr. Fig. 2 shows the disc birthrate parameter $b$ subdivided by galaxy type as a function of our free parameter $t_{\text{low}}$ that corresponds to the time that infall switches on. The dotted line indicates the median value of birthrate parameter while the dashed lines show the quartiles of birthrate parameter presented in Kennicutt et al. (1994). In Table 3, we present the value of the free parameter $t_{\text{low}}$ we adopt in order to reproduce the median value of birthrate parameter for each type of disc galaxy.

To make our results more useful for observers, we fit Gaussians to the $b$ parameter dispersion for each type of disc galaxy (Fig. 1). The full width at half-maximum for each different Gaussian equals the width of the $t_{\text{low}}$ parameter distribution in order to reproduce the quartiles of the $b$ parameter distribution presented in Kennicutt et al. (1994). In Table 4, we give the value of $\sigma$ for the Gaussian fits as well as the width in $t_{\text{low}}$ in order to reproduce the quartiles of the $b$ parameter distribution. The width of the $b$ parameter distribution between the quartiles for each type of disc galaxy is presented in the last column.

**Table 4.** The value of $\sigma$ for the Gaussian fits (second column), the width in $t_{\text{low}}$ in order to reproduce the quartiles of the $b$ parameter distribution (third column), and the width of the $b$ parameter distribution between the quartiles of the distributions (fourth column). The values are shown for different types of disc galaxies.

<table>
<thead>
<tr>
<th>Type</th>
<th>$\sigma$</th>
<th>$\Delta t_{\text{low}}$ (Gyr)</th>
<th>$\Delta b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>1.716</td>
<td>4.04</td>
<td>0.1</td>
</tr>
<tr>
<td>Sb</td>
<td>0.386</td>
<td>0.91</td>
<td>0.3</td>
</tr>
<tr>
<td>Sc</td>
<td>0.205</td>
<td>0.48</td>
<td>0.6</td>
</tr>
<tr>
<td>Sd</td>
<td>0.183</td>
<td>0.43</td>
<td>0.4</td>
</tr>
<tr>
<td>Sm</td>
<td>0.270</td>
<td>0.64</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**Table 3.** Median value of $b$ and $t_{\text{low}}$ values for different models.

<table>
<thead>
<tr>
<th>Type</th>
<th>$b$ (median)</th>
<th>$t_{\text{low}}$ (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td>Sb</td>
<td>0.37</td>
<td>7.00</td>
</tr>
<tr>
<td>Sc</td>
<td>1.04</td>
<td>8.05</td>
</tr>
<tr>
<td>Sd</td>
<td>0.63</td>
<td>7.80</td>
</tr>
<tr>
<td>Sm</td>
<td>1.31</td>
<td>8.35</td>
</tr>
</tbody>
</table>

**Figure 3.** The evolution of the gas surface densities for different ages and different types of disc galaxies. The results are shown for ages (top to bottom panel) of 0, 0.1, 1, 3, 6 and 10 Gyr (dashed line).
Visible stars other than M stars contribute (count the scatter in the measurements of Milky Way scalelength (2001) and are in good agreement with Sb model. Taking into account the scatter in the measurements of Milky Way scalelength (2001) using Hubble Space Telescope observations of M stars in the Galactic disc determine a surface density of $12.2 - 14.3 \, M_\odot \, pc^{-2}$. Visible stars other than M stars contribute $\approx 15 \, M_\odot \, pc^{-2}$, resulting in a total stellar surface density in the range of $\approx 27 - 30 \, M_\odot \, pc^{-2}$.

0, 0.1, 1, 3, 6 and 10 Gyr (dashed line). The SFRs are initially high and hence the time-scale for star formation is short. Almost the total amount of gas in the central region of disc is transformed to stars in $10^7$ yr. The SFR declines rapidly after 1 Gyr. As Figs 3 and 4 show the star formation at early times is concentrated to the inner parts of the disc which have a high surface density, and hence the gas distribution develops a surface density profile with an inner ‘hole’, similar to what is seen in the H I distributions in real galaxies (Deul & den Hartog 1990).

Model Sa has parameters similar to those of the Milky Way. Gas surface densities from direct observations at the solar neighbourhood is $8 \pm 5 \, M_\odot \, pc^{-2}$ (Dame 1993) in good agreement with the predictions of the model. Slightly higher values of $\approx 13 - 14 \, M_\odot \, pc^{-2}$ have been reported by Olling & Merrifield (2001) and are in good agreement with Sb model. Taking into account the scatter in the measurements of Milky Way scalelength ($r_d \approx 2.5 - 3.5 \, kpc$, Sackett 1997) Sb model can also be a good candidate for the Milky Way.

Direct observations of the stars at the solar neighbourhood of Milky Way by Gould, Bahcall & Flynn (1996) and Zheng et al. (2001) using Hubble Space Telescope observations of M stars in the Galactic disc determine a surface density of $12.2 - 14.3 \, M_\odot \, pc^{-2}$. Visible stars other than M stars contribute $\approx 15 \, M_\odot \, pc^{-2}$, resulting in a total stellar surface density in the range of $\approx 27 - 30 \, M_\odot \, pc^{-2}$.

This value is in good agreement with predictions from Sa and Sb models.

2.12.3 Gas velocity profiles

Fig. 5 shows the radial distribution of the gas velocity at 10 Gyr for different types of disc galaxies, Sa (solid line), Sb (thick solid line), Sc (dashed line) and Sm (dotted line). Gas velocity profiles are in good agreement with recent theoretical predictions (Ricotti & Ferrara 2002) that in a multiphase low-metallicity (Z $\approx 5 \times 10^{-3} \, Z_\odot$) ISM the velocity probability distribution should be close to a Maxwellian with velocity dispersion $\sigma \geq 11 \, km \, s^{-1}$, $ec^{-1}$. Furthermore, studies of nearby face-on galaxies show that the velocity dispersion in the H I layer is decreasing monotonically from about 10–13 km s$^{-1}$ in the optically bright inner regions to 6–8 km s$^{-1}$ in the very outer parts (Kamphuis & Sancisi 1993).

2.12.4 Star formation profiles

Fig. 6 shows the evolution of the radial distribution of the SFR for different ages and different types of disc galaxies. The results are shown for ages of 0.1 (solid line), 1 (solid thick line), 3 (dashed line), 6 (dashed thick line) and 10 Gyr (dotted line).

2.12.5 Metallicity profiles

Fig. 7 shows the evolution of the radial distribution of gas metallicity for different ages and different types of disc galaxies. The results are shown for ages of 0.1 (solid line) and 10 Gyr (dotted line). Note the very high value of metallicity for Sa-type galaxies today. The model predicts that metal-rich winds are needed especially for Sa-type galaxies in order to produce reasonable values for metallicity today. This prediction is in agreement with suggestions presented in Dalcanton (2007) (for more detailed comments see Section 3.2).3

3 Note that metallicity today does decline slightly close to the centre. This is due to the radial profile we choose for the infall rate since we add most of the fresh low-metallicity gas to the central regions.
2.12.6 Infall rate profiles

The evolution of the radial distribution of the infall rate (in units of $M_\odot pc^{-2} Gyr^{-1}$) is shown in Fig. 8. The results are shown for different ages. As already mentioned the time when the infall switches on is defined by the free parameter $t_{low}$. For the results presented in Fig. 8, we adopt for $t_{low}$ a value that reproduces the median value of birth parameter $b$ for each type of disc galaxy. For Sa galaxies the results are shown for 3 (solid line) and 6 Gyr (dashed line). Infall rates for Sb, Sc, Sd and Sm galaxies are presented for ages of 8.5 (solid line) and 10 Gyr (dashed line). Note the different range in the y-axis for different types of disc galaxies. An infall rate takes very high values for the Sb, Sc, Sd and Sm galaxies. Since these galaxies have smaller mass and the infall is switched on much later in comparison with the Sa type, we need high infall rates in order to reproduce the observed total mass density in the solar neighbourhood.

2.12.7 Disc global properties

Fig. 9 shows the net SFR across the disc (upper panel) and the evolution of gas fraction and total disc mass, stars plus gas (middle panels), for different types of disc galaxies.

2.13 Star formation rate histories

In this section, we present results for the SFR history at galactocentric radius $r = 1$ kpc for different types of disc galaxies.

3 REFINEMENTS OF THE MODEL

The model described in the previous section contain a number of simplifications, which we will attempt to refine in this section. We introduce some simple improvements to the outflow model (Section 3.1) and to the chemical evolution model (Section 3.2).
Disc galaxy evolution along the Hubble sequence

3.1 Outflow model

In Section 2.8 we assumed that the $k$ parameter is constant. Instead of keeping the $k$ parameter in the outflow model constant for different types of disc galaxies, we can assume that $k$ is proportional to the ratio of bulge-to-disc circular velocities. This is a reasonable assumption especially if we believe that AGN feedback contributes to the wind mechanism. For systems with constant density, the bulge-to-disc velocity ratio can be reduced to the following expression:

$$ \frac{v_b}{v_d} \propto \left( \frac{r_e}{r_d} \right)^{1/a}, \quad (27) $$

where $r_e$ is the effective radius of the bulge and $r_d$ is the disc scalelength. Following MacArthur, Courteau & Holtzman (2003), we can use the following expression for the $r_e/r_d$ ratio:

$$ \frac{r_e}{r_d} = 0.20 - 0.013(T - 5), \quad (28) $$

where $T$ defines the galaxy type. The relationship between $T$ and galaxy type is shown in Table 5. Note that equation (28) is valid only for galaxies with numerical type $T$ between 1 and 7. An initial investigation of equation (28), using $a = 1$ and 2, shows that our results are insensitive to this refinement of the model. We plan to investigate the implications of equation (28) in more detail in a future paper.

3.2 Chemical evolution

In Section 2.10, we assumed that gas ejected from the disc has the same metallicity as the ISM at the time that the gas was ejected. Due to this assumption, the predicted metallicity curve for Sa and Sb galaxies today is very high (see Fig. 7, top panel). This problem does not appear in smaller galaxies (Sc, Sd, Sm) because the infall rate is higher than the rate of star formation, thus allowing the accreted metal-poor gas to dilute the ISM faster than it can be enriched by evolving stars. A comparison with observational data (Pilyugin,
Vilchez & Contini 2004; Kewley, Jansen & Geller 2005) leaves metal-rich outflows as the only viable mechanism for producing the low effective yields observed in gas-rich galaxies. Following Dalcanton (2007), we parametrize the metallicity $Z_{SN}$ of the SN ejecta as a multiple $\eta$ of the nucleosynthetic yield. For a Salpeter IMF $\eta = 6.2 - 7.1$. For this paper, we adopt a value $\eta = 4.25$ for Sa-type galaxies and a smaller value $\eta = 2$ for the other galaxy types. Furthermore, in this improved model for chemical evolution for the accreted gas, we adopt a metallicity of $Z_F = 0.1 \times Z_\odot$. The equation of galactic chemical evolution is

$$
\Sigma_g \, dZ = \left[ p \psi \, dr + (Z_F - Z) \right] f \, dr - Z(\eta - 1) M_w \, dr.
$$

(29)

In Fig. 10, we show the evolution of the radial distribution of gas metallicity for different ages and different types of disc galaxies. The results are shown for ages of 0.1 (solid line) and 10 Gyr (dashed line). Comparison between the model predictions and the observational data is shown in Fig. 11. The results come from Kewley et al. (2005), and the plus points correspond to the improved model predictions.

![Figure 10](https://example.com/figure10.png)

**Figure 10.** The evolution of the radial distribution of metallicity for different ages and different types of disc galaxies. The results are shown for ages of 0.1 (solid line) and 10 Gyr (dashed line).

![Figure 11](https://example.com/figure11.png)

**Figure 11.** The integrated metallicity is plotted versus morphological type. Observational data (diamond points) come from Kewley et al. (2005), and the plus points correspond to the improved model predictions.

![Figure 12](https://example.com/figure12.png)

**Figure 12.** Radial metallicity distribution of the gas after 10 Gyr (dashed line). The solid lines indicate metallicity slopes at the solar radius. Sa [d log(Z)/dr = −0.055 dex kpc$^{-1}$], Sb [d log(Z)/dr = −0.06 dex kpc$^{-1}$], Sc [d log(Z)/dr = −0.065 dex kpc$^{-1}$], Sd [d log(Z)/dr = −0.1 dex kpc$^{-1}$] and Sm [d log(Z)/dr = −0.11 dex kpc$^{-1}$].

(Chiappini, Matteucci & Romano 2001). Our models predict that the metallicity gradient at the solar radius of the discs depends on the type, and increases as we go from early spirals to later types in agreement with observations (Marquez et al. 2002). Our predictions for the metallicity gradient of later-type disc galaxies are in reasonable agreement with observations (Vila-Costas & Edmunds 1992) although there is a considerable scatter in the published values (see Table 6).
Disc galaxy evolution along the Hubble sequence  655

The major shortcoming of the present model is the failure of the chemical enrichment model to reproduce the observed values for nuclear metallicities. Our model predicts very high values for metallicities close to the disc centre for Sa and Sb galaxies whereas the predicted nuclear metallicities for Sd and Sm galaxies are quite low. This is probably due to the high SFRs that the model predicts in the first $10^9$ yr, due to our implicit assumption that the entire gas disc has formed instantaneously at $t = 0$. The extremely high initial SFR results in highly enriched central regions, so enriched that the fresh low metallicity accreted gas cannot dilute the gas efficiently. This is the case especially in galaxies like Sa and Sb characterized by small infall rates. In galaxy types like Sd and Sm, the very high infall rates in the central regions (due to the functional form we assume for the infall model: see Section 2.6) are enough to dilute metals and result in low values for nuclear metallicities. However, the chemical evolution model is in good agreement with observations in terms of the integrated metallicities.

In a future paper, we will develop this model further. Along with the improvements mentioned above, we intend to examine the effect of AGN feedback and compare with numerical simulations.

REFERENCES
Genzel R. et al., 2006, Nat, 442, 786

4 DISCUSSION
We have presented a model of global star formation incorporating SN feedback, gas accretion and enriched outflows in discs modelled by a multiphase ISM in a fixed gravitational potential.

A key prediction of this model is that star formation histories of different types of disc galaxies can be explained in a simple sequence of models which are primarily regulated by the cold gas accretion history. The distributions of disc birth parameters presented in Kennicutt et al. (1994) are reproduced using the parameter $t_{low}$ which varies with the type of disc galaxy. Sa galaxies are characterized by quiescent evolution and a small value for the $t_{low}$ parameter whereas Sb, Sc, Sd and Sm galaxies are characterized by starbursts and relatively large values for the $t_{low}$ parameter.

A description of disc evolution in which the onset and duration of the gas infall history are found to be the controlling parameters is in qualitative agreement with standard ΛCDM cosmology which predicts that protodiscs reside in dark haloes with masses $\sim 10^{12} M_\odot$ and are in a phase of strong gas accretion with values > $10 M_\odot$ yr$^{-1}$ (see e.g. Genzel et al. 2006).

The mass assembly of galaxies occurs through two main processes: hierarchical merging of smaller entities, and more diffuse gas accretion. The relative importance of the two processes cannot be easily found by cosmological simulations, since many physical parameters such as gas dissipation, star formation and feedback, are still unknown.

There are at least some 20 examples of galaxies which in H i show either signs of interactions and/or have small companions (Sancisi 1999). This suggests that galaxies often are in an environment where material for accretion is available. Characteristic examples are the companions NGC 4565–4565A (Rupen 1991) and NGC 4027–4027A (Phookun et al. 1992). These companions have systematic velocities close to those of the main galaxy and H i masses less than 10 per cent of the main galaxy. The H i picture suggests the capture of a gas rich dwarf by a massive system probably to be followed by tidal disruption and accretion of the dwarf. Such examples have been seen also in the Milky Way. The discovery of the Sagittarius dwarf galaxy (Ibata, Gilmore & Irwin 1994) shows that accretion is still taking place at the present time.

The model presented here predicts that metal-rich winds are needed especially for Sa-type galaxies in order to produce reasonable values for the metallicity today. This prediction is in agreement with suggestions presented in Dalcanton (2007) (for more detailed comments see Section 3.2).

Table 6. The best-quality data from Vila-Costas & Edmunds (1992). Columns are as follows. (1) Galaxy name. (2) Galaxy type. (3) Slope in dex kpc$^{-1}$. (4) Quality indicator of the oxygen abundance data. The best data are given by A. (5) Number of H i regions for which there are abundance determinations.

<table>
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<th>Galaxy name</th>
<th>Type</th>
<th>Slope (dex kpc$^{-1}$)</th>
<th>Quality</th>
<th>H i regions</th>
</tr>
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<tbody>
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<td>A</td>
<td>19</td>
</tr>
<tr>
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<td>Sd</td>
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<td>A/B</td>
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