

Chapter 2

The Galaxy Formation Model

2.1 Introduction

In this thesis we focus on modelling star formation (SF), the interstellar medium and SNe feedback in the context of a theory of galaxy formation. The starting point is the semi-analytic model GALFORM in which galaxy formation and evolution are treated in the context of the hierarchical growth paradigm (Cole et al. 2000; Benson et al. 2003; Baugh et al. 2005; Bower et al. 2006; Benson and Bower 2010).

The GALFORM model takes into account the main physical processes that shape the formation and evolution of galaxies. These are: (i) the collapse and merging of dark matter (DM) halos, (ii) the shock-heating and radiative cooling of gas inside DM halos, leading to the formation of galactic disks, (iii) quiescent star formation in galaxy disks, (iv) feedback from supernovae (SNe), heating by active galactic nuclei (AGN) and feedback from photo-ionization of the intergalactic medium (IGM), (v) chemical enrichment of stars and gas, and (vi) galaxy mergers driven by dynamical friction within common DM halos which can trigger bursts of SF, and lead to the formation of spheroids (for a review of these ingredients see Baugh 2006; Benson 2010). Galaxy luminosities are computed from the predicted SF and chemical enrichment histories using a stellar population synthesis model. Dust extinction at different wavelengths is calculated self-consistently from the gas and metal contents of each galaxy and the predicted scale lengths of the disk and bulge components using a radiative transfer model (see Cole et al. 2000 and Lacey et al. 2011). A schematic view of the interplay between these physical processes is shown in Fig. 2.1. Here we have coloured the part of the model on which this thesis focuses. We summarise the main considerations and details in the calculation of each of the physical processes included in GALFORM in this chapter.

One of the key aims of this thesis is to revise the parametrisations used to describe SF and SNe feedback based on physical models of the interstellar medium and recent observational constraints on the SF law in local galaxies. However, it is important at this stage of the thesis to clearly state the physical prescriptions of GALFORM before introducing the major developments presented in this thesis.

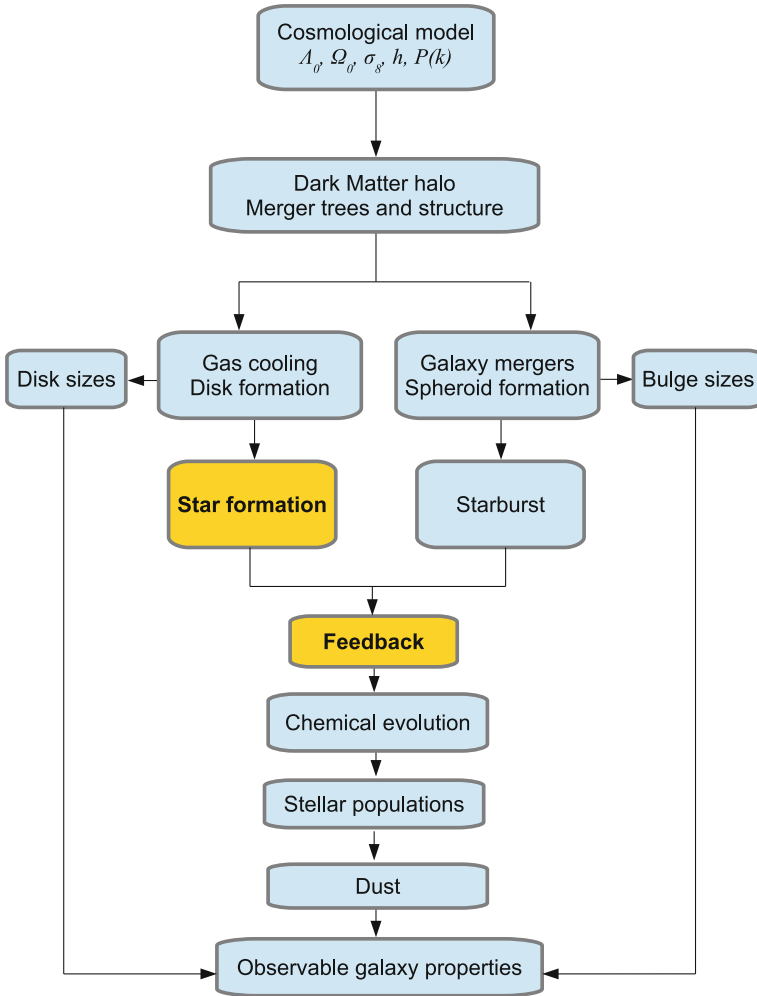


Fig. 2.1 Schematic view of the physical processes considered in GALFORM, adapted from Baugh (2006). Galaxies are assumed to form embedded in DM halos and therefore the first step is to set the cosmological paradigm. This thesis focuses on the interstellar medium, SF and SNe feedback in galaxies (marked as a yellow filled box)

Chapters 3 and 4 make use of two models of GALFORM to analyse the effect of changing the SF law on galaxy properties, such as the molecular and atomic gas contents. These two models are those of Baugh et al. (2005) and Bower et al. (2006). The modelling of some physical processes in these two models is different and in the descriptions given in the next sections of this chapter we state the differences between the two models. In Chap. 4, we introduce our new GALFORM model which makes use of the developments of this thesis and apply the model further in Chaps. 5 and 6.

This chapter is organised as follows. In Sect. 2.2, we describe the cosmological paradigm, the growth of structures and define relevant halo properties used in the galaxy formation theory. Section 2.3 describes the calculation of gas cooling, Sect. 2.4 outlines the treatment of SF, chemical enrichment and SNe feedback in GALFORM before this Thesis was carried out, Sect. 2.5 describes the modelling of AGN and photoionisation feedback, Sect. 2.6 describes the handling of galaxy mergers and disk instabilities in the model, Sect. 2.7 summarises how sizes are calculated in GALFORM and Sect. 2.8 gives an overview of the calculation of the spectral energy distribution of galaxies. Finally, Sect. 2.9 reviews for clarity the differences between the Baugh et al. (2005) and Bower et al. (2006) model.

2.2 Formation and Growth of Dark Matter Structures

In the standard cosmological picture Λ cold DM (Λ CDM), the universe is composed of two forms of energy: matter (including dark and baryonic matter) and dark energy. In the Λ CDM picture, the dark energy is a cosmological constant characterised by an equation of state $\omega = P/\rho = -1$ (in natural units), where P is the pressure and ρ is the energy density. The contributions to the total energy density of the Universe from dark energy, DM and baryons are Ω_Λ , Ω_M and Ω_b , where $\Omega_\Lambda + \Omega_M + \Omega_b \equiv 1$, according to the position of the first harmonic peak in the power spectrum of temperature fluctuations of the CMB. The expansion of the Universe is characterised by the Hubble parameter H_0 . Perturbations in the density of the Universe are well described by a scale-free primordial power spectrum with power-law index n_s and amplitude σ_8 .

We now summarise the three main aspects of structure formation in a hierarchical growth cosmogony that are relevant for the theory of galaxy formation: (i) the halo mass function of DM halos at a given time, (ii) the formation history, or merger tree, of DM halos and (iii) the properties of individual halos. There are two ways to generate the information above: through Monte Carlo trees making use of the Press and Schechter (1974) theory and its extension to give progenitor distributions (Bond et al. 1991; White and Frenk 1991; Lacey et al. 1993; Cole et al. 2000; Baugh et al. 2005; Parkinson et al. 2008) or through N -body simulations (Springel et al. 2005; Bower et al. 2006). The later has been growing in popularity in recent years due to the advantage of assigning positions to galaxies, which is useful for studies of galaxy clustering, and with the availability of large volume, high-resolution N -body simulations.

We now describe theoretically how the aspects above are calculated. The descriptions in (i) and (ii) are relevant only for the case of Monte Carlo simulations, given that in N -body simulations these properties are calculated directly, while (iii) is relevant for both Monte Carlo and N -body simulations (although with some technical differences related to the calculation of e.g. density profiles).

2.2.1 The Halo Mass Function

It is possible to associate halos with the peaks in a Gaussian random field of matter, which represents the conditions in the early universe. Based on statistics of Gaussian random fields, Press and Schechter (1974) derived an analytical approximation to the mass function for DM halos, in which the number of halos per unit volume with masses between M and $M + dM$ is

$$\frac{dn}{dM}(t) = \sqrt{\frac{2}{\pi}} \frac{\bar{\rho}}{M^2} \frac{\delta_c(t)}{\sigma(M)} \left| \frac{d \ln, \sigma}{d \ln M} \right| \exp \left(-\frac{\delta_c^2(t)}{2 \sigma^2(M)} \right), \quad (2.1)$$

where $\bar{\rho}$ is the mean density of the Universe, $\sigma(M)$ is the root mean variance in the linear density field smoothed using a top-hat filter that contains, on average, a mass M , and $\delta_c(t)$ is the critical linear perturbation theory overdensity for a spherical top-hat collapse at a time t .

2.2.2 Halo Merger Trees

The Press and Schechter (1974) theory can be extended to include information about the fraction of halos of mass M_2 , at a time t_2 , which at an earlier time t_1 , was in halos of mass in the range M_1 to $M_1 + dM_1$, denoted by $f_{12}(M_1, M_2)$ (Bond et al. 1991; Bower 1991),

$$f_{12}(M_1, M_2) dM_1 = \frac{1}{\sqrt{2\pi}} \frac{\delta_{c1} - \delta_{c2}}{(\sigma_1^2 - \sigma_2^2)^{3/2}} \exp \left[-\frac{(\delta_{c1} - \delta_{c2})^2}{2(\sigma_1^2 - \sigma_2^2)} \right] \frac{d\sigma_1^2}{dM_1} dM_1. \quad (2.2)$$

Here, δ_{c1} and δ_{c2} are the critical threshold on the linear overdensity for collapse at t_1 and t_2 , respectively, and σ_1^2 and σ_2^2 are the mass variance in linear theory in spheres enclosing mass M_1 and M_2 , respectively. The way to calculate these parameters is described in e.g. Lacey et al. (1993). It is possible to take Eq. 2.2 in the limit that t_1 and t_2 are similar or close together in order to track the average mass fraction of a halo of mass M_2 which was in halos of mass M_1 at slightly earlier times $t_2 - dt$. From this, it is possible to estimate for M_2 the mean number of objects of mass M_1 that the current halo is composed of, therefore giving the mass distribution for the progenitors of M_2 with time,

$$\frac{dN}{dM_1} = \sqrt{2\pi} \left| \frac{d \ln, \sigma}{d \ln M_1} \right| M_2 \frac{\sigma_1^2}{M_1^2} \frac{\delta_{c1} - \delta_{c2}}{(\sigma_1^2 - \sigma_2^2)^{3/2}} \exp \left[-\frac{(\delta_{c1} - \delta_{c2})^2}{2(\sigma_1^2 - \sigma_2^2)} \right]. \quad (2.3)$$

During most of this thesis, we make use of N -body trees (partially in Chap. 3 and fully in Chaps. 5 and 6). However, the advantage of using Monte Carlo trees

over N -body simulation, is that this allows us to improve the dynamical range of simulated halos as much as we want. This is particularly important when studying atomic hydrogen in the ISM of galaxies, as we show in Chap. 4. For this reason, partially in Chap. 3 and fully in Chap. 4, we use the DM halo Monte Carlo generator of Parkinson et al. (2008).

The Parkinson et al. scheme is tuned to match merger trees extracted from the N -body Millennium simulation (Springel et al. 2005). The cosmological parameters adopted in the Millennium simulation correspond to those found by WMAP from the first year of observations: $\Omega_m = \Omega_{DM} + \Omega_{baryons} = 0.25$ (giving a baryon fraction of 0.18), $\Omega_\Lambda = 0.75$, $\sigma_8 = 0.9$ and $h = 0.73$ (Spergel et al. 2003). The resolution of the Millennium simulation is fixed at a halo mass of $1.72 \times 10^{10} h^{-1} M_\odot$. In the approach of Parkinson et al. realizations of the merger histories of halos are generated over a range of halo masses. The range of masses simulated changes with redshift approximately as $(1+z)^{-3}$ in order to follow a representative sample of halos, which cover a similar range of abundances at each epoch.

2.2.3 Halo Properties

The halo properties, besides mass, relevant to galaxy formation are the halo virial radius, spin and density profile. The virial radius corresponds approximately to the collapsed radius at which the mean enclosed density is $\Delta = 178$ times the background density (calculated from the spherical collapse model),

$$R_v = \left(\frac{3 M}{4\pi \Delta \bar{\rho}} \right)^{1/3}. \quad (2.4)$$

This radius also characterises the transition between the coherent flow of matter and random motions inside virialized structures, as N -body simulations show (Cole and Lacey 1996).

Tidal torques acting during the formation of the halo (in the collapse period) cause the halo to gain angular momentum. The angular momentum of halos, J_H is typically quantified by the dimensionless spin parameter λ_H ,

$$\lambda_H = \frac{J_H \sqrt{|E_H|}}{G M^{5/2}}, \quad (2.5)$$

where E_H is the energy of the halo which has a mass M . The distribution of λ_H is very well constrained by N -body simulations and it has been shown that it depends very weakly on halo mass and on the form of the initial spectrum of density fluctuations (i.e. weakly dependent on n_s and σ_8 ; e.g. Cole and Lacey 1996; Bett et al. 2010).

In the model, it is assumed that the radial profile of matter in halos is well described by the profile of (Navarro et al. 1997) (NFW). Although recent N -body studies have suggested that the density of DM halos is better described by an Einasto (1965)

profile rather than a NFW profile, the accuracy of the latter is good enough for the purposes of this thesis (e.g. Merritt et al. 2005; Prada et al. 2006). We follow the description of Cole et al. (2000), in which halos are allowed to contract in response to the presence of baryons. The galaxy disk, bulge and DM halo adjust to each other adiabatically.

The radial density of DM for $r \leq R_v$ is described by a NFW profile as,

$$\rho_{\text{DM}}(r) = \frac{\Delta \bar{\rho}}{f(a_{\text{NFW}})} \frac{1}{(r/R_v)(a_{\text{NFW}} + r/R_v)^2}, \quad (2.6)$$

where $a_{\text{NFW}} = R_{\text{NFW}}/R_v$ is the ratio between the scale length, R_{NFW} , and the virial radius, R_v , $f(a_{\text{NFW}}) = \ln(1 + 1/a_{\text{NFW}}) - 1/(1 + a_{\text{NFW}})$ and $\rho_c = 3 H^2/(8\pi G)$ is the critical density of the universe.

The effective rotational velocity of a halo is calculated from its spin and virial velocity, $V_v \equiv \sqrt{GM/R_v}$,

$$V_{\text{rot}} = A(a_{\text{NFW}}) \lambda_H V_v, \quad (2.7)$$

where $A(a_{\text{NFW}})$ is a dimensionless function of a_{NFW} , which is well fitted by $A(a_{\text{NFW}}) \approx 4.1 + 1.8 a_{\text{NFW}}^{5/4}$, in the range $a_{\text{NFW}} = 0.03-0.4$ (Cole et al. 2000).

We use the virial velocity to estimate the virial temperature of the halo as,

$$T_v = \frac{1}{2} \frac{\mu m_H}{k_B} V_v^2, \quad (2.8)$$

where μ is the mean molecular mass, m_H is the mass of the hydrogen atom and k_B is the Boltzmann constant.

The properties of DM halos above are relevant in the calculation of the halo gas circular velocity and angular momentum, the disk size, the rotation velocity of the disk and the cooling time.

2.3 Gas Cooling in Halos

Galaxies form from gas which cools from the hot halo observing conservation of angular momentum. As the temperature decreases, thermal pressure stops supporting the gas which therefore settles in a disk. This gives rise to rotating disks (Fall and Efstathiou 1980).

Observations and hydrodynamical simulations show that the hot gas does not follow the DM profile in the inner regions of the halo, but instead is characterised by a core radius inside which the density stops rising. The gas profile of the hot gas is typically modelled with a β profile (Cavaliere and Fusco-Femiano 1976),

$$\rho_{\text{hot}}(r) \propto (r^2 + r_{\text{core}}^2)^{-3\beta_{\text{fit}}/2}, \quad (2.9)$$

The simulations of Eke et al. (1998) show that $\beta_{\text{fit}} \approx 2/3$ and that $r_{\text{core}}/R_{\text{NFW}} \approx 1/3$. In GALFORM, we adopt the values above and use $\rho_{\text{hot}}(r) \propto (r^2 + R_{\text{NFW}}^2/9)^{-1}$.

Given the hot gas density, we calculate the cooling time as a function of radius,

$$\tau_{\text{cool}}(r) = \frac{3}{2} \frac{\mu m_{\text{H}} k_{\text{B}} T_{\text{hot}}}{\rho_{\text{hot}}(r) \Lambda(T_{\text{hot}}, Z_{\text{hot}})}, \quad (2.10)$$

where $\Lambda(T_{\text{hot}}, Z_{\text{hot}})$ is the cooling function that depends on the gas temperature and the metallicity Z_{hot} (i.e. the ratio between the mass in metals heavier than Helium and total gas mass), and temperature of the hot gas corresponds to the virial temperature of the halo, $T_{\text{hot}} = T_{\text{V}}$. The cooling rate per unit volume is $\epsilon_{\text{cool}} \propto \rho_{\text{hot}}^2 \Lambda(T_{\text{hot}}, Z_{\text{hot}})$. In GALFORM we adopt the cooling function tabulated by Sutherland and Dopita (1993). This allows the gas to cool via two-body collisional radiative processes, which correspond to collisional excitation and Bremsstrahlung radiation.

During a timestep δt in the integration of galaxy properties, we calculate the amount of gas that cools and estimate the radius at which $\tau_{\text{cool}}(r_{\text{cool}}) = t - t_{\text{form}}$, where t_{form} corresponds to the time at which the halo was formed and t to the current time. The gas inside r_{cool} is cool enough to be accreted onto the disk. However, in order to be accreted onto the disk, the cooled gas should have had enough time to fall onto the disk. Thus, the gas that has enough time to cool and be accreted onto the disk is that within the radii in which the free-fall time and the cooling time are smaller than $(t - t_{\text{form}})$, defined as r_{ff} and r_{cool} , respectively. The mass accreted onto the disk simply corresponds to the hot gas mass enclosed within $r = \min[r_{\text{cool}}, r_{\text{ff}}]$.

2.4 Star Formation, Chemical Enrichment and Supernova Feedback

The SF activity in GALFORM is regulated by three channels: (i) accretion of gas which cools from the hot gas halo onto the disk, (ii) SF from the cold gas and, (iii) reheating and ejection of gas due to SNe feedback. These channels modify the mass and metallicity of each of the baryonic components (i.e. stellar mass, $M_{\star}$, cold gas mass, M_{cold} , hot halo gas mass, M_{hot} , and their respective masses in metals, $M_{\star}^Z$, M_{cold}^Z and M_{hot}^Z). The system of equations relating these quantities is Cole et al. (2000):

$$\dot{M}_{\star} = (1 - R)\psi \quad (2.11)$$

$$\dot{M}_{\text{cold}} = \dot{M}_{\text{cool}} - (1 - R + \beta)\psi \quad (2.12)$$

$$\dot{M}_{\text{hot}} = -\dot{M}_{\text{cool}} + \beta\psi \quad (2.13)$$

$$\dot{M}_{\star}^Z = (1 - R)Z_{\text{cold}}\psi \quad (2.14)$$

$$\dot{M}_{\text{cold}}^Z = \dot{M}_{\text{cool}}Z_{\text{hot}} + (p(1 - e) - (1 + \beta - R)Z_{\text{cold}})\psi \quad (2.15)$$

$$\dot{M}_{\text{hot}}^Z = -\dot{M}_{\text{cool}}Z_{\text{hot}} + (pe + \beta Z_{\text{cold}})\psi. \quad (2.16)$$

Here ψ denotes the instantaneous SFR, $\dot{M}_{\text{cool}}$ the cooling rate, β the ratio between the outflow mass rate due to core collapse SNe (SNe cc) and ψ (the efficiency of stellar feedback; Sect. 2.4.2), p denotes the yield (the fraction of mass converted into stars that is returned to the ISM in the form of metals), e is the fraction of newly produced metals ejected directly from the stellar disk to the hot gas phase, R is the fraction of mass recycled to the ISM (in the form of stellar winds and SN explosions), $Z_{\text{cold}} = M_{\text{cold}}^Z / M_{\text{cold}}$ is the metallicity of the cold gas, and $Z_{\text{hot}} = M_{\text{hot}}^Z / M_{\text{hot}}$ is the metallicity of the hot halo gas. Descriptions of the feedback mechanisms can be found in Benson et al. (2003) and Lacey et al. (2008). These equations are defined as a function of ψ , which in all previous versions of GALFORM has the forms described in Sect. 2.4.1, with $\psi \propto M_{\text{cold}}$. This form of the SFR has the advantage that Eqs. 2.15–2.20 can be solved analytically assuming that $\dot{M}_{\text{cool}}$ is constant over a timestep.

Below we describe the way ψ , β , R and p are calculated.

2.4.1 The Original Star Formation Laws in GALFORM

The original GALFORM models use a parametric SF law to compute the quiescent SFR in galaxy disks at each timestep (Cole et al. 2000)

$$\psi = \frac{M_{\text{cold}}}{\tau_{\star}}, \quad (2.17)$$

where M_{cold} is the total cold gas mass in the galactic disk and $\tau_{\star}$ is the timescale for the SF activity which may depend on galaxy parameters but not on the gas mass. This choice was motivated by the observations of K98 (see Bell et al. 2003a). The SF timescale in Eq. 2.17 was parametrized by Cole et al. (2000) as,

$$\tau_{\star} = \frac{\tau_{\text{disk}}}{\epsilon_{\star}} [V_{\text{circ}}(r_{\text{d}}) / V_0]^{\alpha_{\star}}, \quad (2.18)$$

where $V_0 = 200 \text{ km s}^{-1}$, $V_{\text{circ}}(r_{\text{d}})$ is the disk circular velocity at the half mass radius, r_{d} , $\tau_{\text{disk}} = r_{\text{d}} / V_{\text{circ}}(r_{\text{d}})$ is the disk dynamical timescale, and $\epsilon_{\star}$ and $\alpha_{\star}$ are free parameters, with values originally chosen to reproduce the gas-to-luminosity ratio observed in local spiral galaxies (Cole et al. 2000). Bower et al. (2006) adopted values of $\epsilon_{\star} = 0.0029$ and $\alpha_{\star} = -1.5$, mainly to reproduce the galaxy LF, without particular reference to the cold gas to luminosity ratio (see Kim et al. 2011).

In the Baugh et al. (2005) model a different SF timescale was adopted, in order to reduce the amount of quiescent SF activity at high redshift, thereby allowing more SF in bursts. The recipe used in the Baugh et al. (2005) model is

$$\tau_{\star} = \tau_0 [V_{\text{circ}}(r_{\text{d}}) / V_0]^{\alpha_{\star}}, \quad (2.19)$$

where $V_0 = 200 \text{ km s}^{-1}$, τ_0 and α are free parameters set to $\tau_0 = 8 \text{ Gyr}$ and $\alpha_\star = -3$, in order to match the local gas mass to luminosity ratio (see Power et al. 2010).

During starbursts (SBs) caused by galaxy mergers and, in the case of the Bower et al. (2006) model, also by disk instabilities, the available reservoir of cold gas is assumed to be consumed in the SB event with a finite duration. The SF timescale in bursts is taken to be $f_{\text{dyn}} \tau_{\text{bulge}}$, with τ_{bulge} being the bulge dynamical time, with a floor value $\tau_{\text{*burst,min}}$. Baugh et al. 2005 adopted $f_{\text{dyn}} = 50$ and $\tau_{\text{*burst,min}} = 0.2 \text{ Gyr}$ while Bow06 used $f_{\text{dyn}} = 2$ and $\tau_{\text{*burst,min}} = 0.005 \text{ Gyr}$.

2.4.2 The Efficiency of Stellar Feedback

The original model uses a simple parametric form to include SNe feedback (which refers to feedback from core collapse SNe). The outflow rate driven by SNe is taken to be proportional to the SFR, ψ ,

$$\dot{M}_{\text{reheated}} = \beta \psi, \quad (2.20)$$

where β is parametrised as,

$$\beta = \left(\frac{V_{\text{circ}}}{V_{\text{hot}}} \right)^{-\alpha}. \quad (2.21)$$

Here V_{circ} corresponds to the circular velocity of the disk or the bulge of each galaxy (that characterises the potential well depth of the galaxy), and V_{hot} and α are free-parameters. Values of $\alpha = 1$ and $\alpha = 2$ represent “momentum-conserving” and “energy-conserving” winds, respectively. Different values have been adopted in the literature. Cole et al. (2000) adopted $\alpha = 2$ and $V_{\text{hot}} = 200 \text{ km s}^{-1}$, which were chosen to fit the faint-end of the luminosity function in the b_J - and K-bands and the Tully-Fisher relation (see Figs. 6 and 7 in Cole et al. 2000). In the case of the Baugh et al. (2005) and Bower et al. (2006) models, different values were adopted for α and V_{hot} , which is unsurprising given that both papers made large modifications to the feedback scheme either by implementing a superwind scheme in the case of Baugh et al. (2005), and AGN feedback in the case of Bower et al. (2006). Also these models used a higher baryon density compared to Cole et al. reflecting the improving constraints on cosmological parameters since this earlier work. The values adopted in each model are $\alpha = 2$ and $V_{\text{hot}} = 300 \text{ km s}^{-1}$, and $\alpha = 3.2$ and $V_{\text{hot}} = 485 \text{ km s}^{-1}$, respectively.

The gas expelled from galaxies by SN feedback is assumed to be reincorporated into the hot halo after a few dynamical times in the Bower et al. (2006) model. In the Baugh et al. (2005) model, this gas reincorporation happens only after the DM halo doubles its mass. This time, called the halo lifetime, is usually much longer than the dynamical time of the halo.

In the case of the Baugh et al. (2005) model, a fraction of the reheated gas by SNe is assumed to be ejected from the halo and is not reincorporated. This is termed ‘superwind’ feedback and was first introduced by Benson et al. (2003). The rate of mass loss from the halo by this mechanism is $f_{\text{sw}}\psi$, where

$$f_{\text{sw}} = \begin{cases} f_{\text{sw},0} & V_{\text{circ}} < V_{\text{sw}}, \\ f_{\text{sw},0} \left(\frac{V_{\text{sw}}}{V_{\text{circ}}} \right)^2 & V_{\text{circ}} \geq V_{\text{sw}}, \end{cases} \quad (2.22)$$

where $V_{\text{sw}} = 200 \text{ km s}^{-1}$ and $f_{\text{sw},0} = 2$ in the Baugh et al. (2005) model.

2.4.3 Recycled Fraction and Yield

For chemical enrichment in GALFORM, we adopt the instantaneous mixing approximations for the metals in the ISM. This implies that the metallicity of the cold gas mass instantaneously absorbs the fraction of recycled mass and newly synthesised metals in recently formed stars, neglecting the time delay for the ejection of gas and metals from stars.

The recycled mass injected back to the ISM by newly born stars is calculated from the initial mass function (IMF) as,

$$R = \int_{m_{\text{min}}}^{m_{\text{max}}} (m - m_{\text{rem}}) \phi(m) dm, \quad (2.23)$$

where m_{rem} is the remnant mass and the IMF is defined as $\phi(m) \propto dN(m)/dm$. Similarly, we define the yield as

$$p = \int_{m_{\text{min}}}^{m_{\text{max}}} m_i(m) \phi(m) dm, \quad (2.24)$$

where $m_i(m)$ is the mass of newly synthesised metals ejected by stars of initial mass m . The minimum and maximum mass in the integrations are taken to be $m_{\text{min}} = 1 M_{\odot}$ and $m_{\text{max}} = 120 M_{\odot}$. Stars with masses $m < 1 M_{\odot}$ have lifetimes longer than the age of the Universe, and therefore they do not contribute to the recycled fraction and yield. We use the stellar evolution model of Marigo (2001) and Portinari et al. (1998) to calculate the ejected mass from intermediate and massive stars, respectively.

The stellar IMF is assumed to be universal in the Bower et al. (2006) model, with the Kennicutt (1983) IMF adopted. The Baugh et al. (2005) model assumes two IMFs, a top-heavy IMF during starbursts (SB) and a Kennicutt IMF during quiescent SF in disks. Defining the IMF as $dN/d \ln m \propto m^{-x}$, the Kennicutt IMF has $x = 0.4$ below $m = 1 M_{\odot}$ and $x = 1.5$ at higher masses, while the top-heavy IMF has $x = 0$ at all masses.

2.5 Other Sources of Feedback

In addition to the SNe feedback outlined above, photoionisation of the IGM in the early Universe and feedback from AGN are also included in GALFORM, and specifically in the Bower et al. (2006) model for the latter case. Both physical processes are described below.

2.5.1 Photoionisation Heating of the IGM

At very early epochs in the Universe, right after the epoch of cosmological recombination, the background light consists of the black body radiation from the CMB. At this stage the universe remains neutral until the first generation of stars, galaxies and quasars start emitting photons and ionising the medium around them. Eventually, the ionised pockets grow and merge. This corresponds to the reionization epoch of the Universe (e.g. Barkana and Loeb 2001). The large ionising radiation density significantly affects small halos, maintaining the baryons at temperatures hotter than the virial temperature, suppressing cooling. In GALFORM, this is included in a simple way: it is assumed that no gas is allowed to cool in haloes with a circular velocity below V_{crit} at redshifts below z_{reion} Benson et al. (2003). Baugh et al. (2005) and Bower et al. (2006) adopt $V_{\text{crit}} = 50\text{--}60 \text{ km s}^{-1}$ and $z_{\text{reion}} = 6$.

2.5.2 AGN Feedback

AGN feedback was introduced into GALFORM by Bower et al. (2006) and replaced the scheme of superwinds included in the Baugh et al. (2005) model, as a more energetically, feasible way of regulating the formation of massive galaxies. AGN feedback is assumed to be effective only in halos undergoing quasi-hydrostatic cooling. In this situation, mechanical energy input by the AGN is expected to stabilise the flow and regulate the rate at which the gas cools. Whether or not a halo is undergoing quasi-hydrostatic cooling depends on the cooling and free-fall times: the halo is in this regime if $t_{\text{cool}}(r_{\text{cool}}) > \alpha_{\text{cool}}^{-1} t_{\text{ff}}(r_{\text{cool}})$, where t_{ff} is the free fall time at r_{cool} , and $\alpha_{\text{cool}} \sim 1$ is an adjustable parameter close to unity. The Bow06 model adopts $\alpha_{\text{cool}} = 0.58$. During radiative cooling, black holes have a growth rate given by $\dot{m}_{\text{BH}} = L_{\text{cool}}/0.2 c^2$, where L_{cool} is the cooling luminosity and c is the speed of light.

AGN are assumed to be able to quench gas cooling only if the available AGN power is comparable to the cooling luminosity, $L_{\text{cool}} < \epsilon_{\text{SMBH}} L_{\text{Edd}}$, where L_{Edd} is the Eddington luminosity of the central black hole and $\epsilon_{\text{SMBH}} \sim 1$ is a free parameter. The Bow06 model adopts $\epsilon_{\text{SMBH}} = 0.04$.

2.6 Galaxy Mergers and Disk Instabilities

Galaxy mergers and disk instabilities give rise to the formation of spheroids and elliptical galaxies. Below we describe both physical processes.

2.6.1 Galaxy Mergers

When DM halos merge, we assume that the galaxy hosted by the most massive progenitor halo becomes the central galaxy, while all the other galaxies become satellites orbiting the central galaxy. These orbits gradually decay towards the centre due to energy and angular momentum losses driven by dynamical friction with the halo material.

Eventually, given sufficient time satellites spiral in and merge with the central galaxy. Depending on the amount of gas and baryonic mass involved in the galaxy merger, a starburst can result. The time for the satellite to hit the central galaxy is called the orbital timescale, τ_{merge} , which is calculated following Lacey et al. (1993) as

$$\tau_{\text{merge}} = f_{\text{df}} \Theta_{\text{orbit}} \tau_{\text{dyn}} \left[\frac{0.3722}{\ln(\Lambda_{\text{Coulomb}})} \right] \frac{M}{M_{\text{sat}}}. \quad (2.25)$$

Here, f_{df} is a dimensionless adjustable parameter which is $f_{\text{df}} > 1$ if the satellite's halo is efficiently stripped early on during the infall, Θ_{orbit} is a function of the orbital parameters, $\tau_{\text{dyn}} \equiv \pi R_v / V_v$ is the dynamical timescale of the halo, $\ln(\Lambda_{\text{Coulomb}}) = \ln(M/M_{\text{sat}})$ is the Coulomb logarithm, M is the halo mass of the central galaxy and M_{sat} is the mass of the satellite, including the mass of the DM halo in which the galaxy was formed.

Cole et al. (2000) used the Θ_{orbit} function calculated in Lacey et al. (1993),

$$\Theta_{\text{orbit}} = \left[\frac{J}{J_c(E)} \right]^{0.78} \left[\frac{r_c(E)}{R_v} \right]^2, \quad (2.26)$$

where J is the initial angular momentum and E is the energy of the satellite's orbit, and $J_c(E)$ and $r_c(E)$ are the angular momentum and radius of a circular orbit with the same energy as that of the satellite, respectively. Thus, the circularity of the orbit corresponds to $J/J_c(E)$. The function Θ_{orbit} is well described by a log normal distribution with median value $\langle \log_{10} \Theta_{\text{orbit}} \rangle = -0.14$ and dispersion $\langle (\log_{10} \Theta_{\text{orbit}} - \langle \log_{10} \Theta_{\text{orbit}} \rangle)^2 \rangle^{1/2} = 0.26$, and its value is not correlated with satellite galaxy properties. Therefore, for each satellite, the value of Θ_{orbit} is randomly chosen from the above distribution. Note that the dependence of Θ_{orbit} on J in Eq. 2.26 is a fit to numerical simulations.

If $\tau_{\text{merge}} < t - t_{\text{form}}$ for a satellite galaxy, we proceed to merge it with the central galaxy at a time t . If the total mass of gas plus stars of the primary (largest)

and secondary galaxies involved in a merger are $M_p = M_{\text{cold},p} + M_{\star,p}$ and $M_s = M_{\text{cold},s} + M_{\star,s}$, the outcome of the galaxy merger depends on the galaxy mass ratio, M_s/M_p , and the fraction of gas in the primary galaxy, $M_{\text{cold},p}/M_p$:

- $M_s/M_p > f_{\text{ellip}}$ drives a major merger. In this case all the stars present are rearranged into a spheroid. In addition, any cold gas in the merging system is assumed to undergo a burst of SF and the stars formed are added to the spheroid component. We typically take $f_{\text{ellip}} = 0.3$, which is within the range found in simulations (e.g. Baugh et al. 1996).
- $f_{\text{burst}} < M_s/M_p \leq f_{\text{ellip}}$ drives minor mergers. In this case all the stars in the secondary galaxy are accreted onto the primary galaxy spheroid, leaving intact the stellar disk of the primary. In minor mergers the presence of a starburst depends on the cold gas content of the primary galaxy.
- $f_{\text{burst}} < M_s/M_p \leq f_{\text{ellip}}$ and $M_{\text{cold},p}/M_p > f_{\text{gas,burst}}$ drives a starburst in a minor merger. The perturbations introduced by the secondary galaxy suffice to drive all the cold gas from both galaxies to the new spheroid, where it produces a starburst. The opposite holds if $M_{\text{cold},p}/M_p < f_{\text{gas,burst}}$. The Baugh et al. (2005) and Bower et al. (2006) models adopt $f_{\text{gas,burst}} = 0.75$ and $f_{\text{gas,burst}} = 0.1$, respectively.
- $M_s/M_p \leq f_{\text{burst}}$ results in the primary disk remaining unchanged. As before, the stars accreted from the secondary galaxy are added to the spheroid, but the overall gas component (from both galaxies) stays in the disk, along with the stellar disk of the primary. The Baugh et al. (2005) and Bower et al. (2006) models adopt $f_{\text{gas,burst}} = 0.05$ and $f_{\text{gas,burst}} = 0.1$, respectively.

2.6.2 Disk Instabilities

If the disk becomes sufficiently massive that its self-gravity is dominant, then it is unstable to small perturbations by minor satellites or DM substructures. The criterion for instability was described by Efsthathiou et al. (1982) and Mo et al. (1998) and introduced in GALFORM by Cole et al. (2000),

$$\epsilon = \frac{V_{\text{circ}}(r_d)}{\sqrt{G M_d/r_s}}. \quad (2.27)$$

Here, $V_{\text{circ}}(r_d)$ is the circular velocity of the disk at the half-mass radius, r_d , r_s is the scale radius of the disk and M_d is the disk mass (gas plus stars). If $\epsilon < \epsilon_{\text{disk}}$ the disk is considered to be unstable. In the case of unstable disks, stars and gas in the disk are accreted onto the spheroid and the gas inflow drives a starburst. The Baugh et al. (2005) model does not include disk instabilities, while the Bower et al. (2006) model does and adopts $\epsilon_{\text{disk}} = 0.8$.

2.7 Galaxy Sizes

The main assumptions used to calculate galaxy sizes in GALFORM are: (i) that the disk is well described by an exponential profile with half-mass radius r_d , (ii) that the bulge is well described by a $r^{1/4}$ De Vacouleurs profile in projection with half-mass radius r_b , (iii) that the DM halo follows a NFW profile that is spherically deformed in response to the gravity of baryons, and (iv) that the mass distribution in the halo and the lengthscales of the disk and the bulge are assumed to adjust adiabatically in response to each other.

In the case of the disk, the size is calculated from conservation of angular momentum and centrifugal equilibrium. The specific angular momentum of the disk, j_d , at r_d must satisfy,

$$\frac{j_d^2}{k_d^2} = G [M(r_d) + k_h M_d(r_d) + M_b(r_d)] r_d, \quad (2.28)$$

where k_h arises from the disk geometry and for an exponential disk $k_h = 1.25$, k_d relates the total angular momentum of the disk to the specific angular momentum of the disk at the half-mass radius, and is $k_d = 1.19$ (see Cole et al. 2000 for derivations of the values of k_h and k_d). In Eq. 2.28, M , M_d and M_b correspond to the mass of the halo, disk and bulge.

In the case of the bulge, the size is determined from energy conservation and virial equilibrium. Similar to the case of the disk, the radius of the bulge is calculated from,

$$j_b^2 = G [M(r_b) + M_d(r_b) + M_b(r_b)] r_b, \quad (2.29)$$

where $j_b = r_b V_{\text{circ}}(r_b)$ is the pseudo-specific angular momentum of the bulge.

In the case of galaxy mergers the resulting radius is calculated from the virial theorem,

$$\frac{(M_s + M_p)^2}{r_{\text{new}}} = \frac{M_s}{r_s} + \frac{M_p}{r_p} + \frac{f_{\text{orbit}}}{d} \frac{M_s M_p}{r_s + r_p}, \quad (2.30)$$

where d and f_{orbit} are estimated from the binding energy of each of the galaxies and the mutual orbital energy, respectively. A value of $d = 0.5$ is adopted, which is valid for both the exponential and the $r^{1/4}$ profiles (i.e. d is very weakly dependent on the density profile), and $f_{\text{orbit}} = 1$, which corresponds to the orbital energy of two point masses moving in a circular orbit with separation $r_p + r_s$.

2.8 The Spectral Energy Distribution of Galaxies

In GALFORM we calculate the spectral energy distribution (SED) of galaxies in two steps: we first calculate the emission from stars and then estimate the absorption of

starlight by dust. These two steps allow us to calculate the SED of galaxies from the far-Ultraviolet (FUV) to the far-Infrared (FIR). Below we describe how these two steps are calculated in GALFORM.

2.8.1 Emission of Light

The emission of light depends on the SF and chemical enrichment history of galaxies, and the assumed IMF. We use stellar population synthesis models to calculate the emission of a stellar population of a given age and metallicity. Because the SED of galaxies depends on the IMF, it is necessary to use two sets of libraries in the case of the Baugh et al. (2005) model, which assumes a top-heavy IMF during starbursts.

2.8.2 Dust Extinction

GALFORM calculates the absorption of starlight by dust and the reemission in Infrared (IR) bands using the method described in Lacey et al. (2011) and Gonzalez-Perez et al. (2012). The dust extinction depends on the dust mass, which is estimated from the cold gas mass and metallicity, assuming a dust-to-gas ratio which is proportional to the gas metallicity. The geometry assumed in the model is a two-phase component for the ISM, diffuse plus clumped gas plus dust. In the case of quiescent SF, the dust is distributed in the disk, while for ongoing starbursts, the dust is considered to have a disk like geometry.

The model assumes that a fraction f_{cloud} of the gas and dust in the ISM is in molecular clouds of mass M_{cloud} and radius r_{cloud} . Stars form inside clouds, and then leak-out to the diffuse medium on a timescale t_{esc} , so that the fraction of stars inside clouds drops from 1 at $t < t_{\text{esc}}$ to 0 at $t > 2t_{\text{esc}}$. The dust extinction inside clouds depends on the surface density of the clouds and the gas metallicity, with the stars treated as being at the centre of the cloud. In the case of the diffuse medium, the extinction is calculated using the tabulated radiative transfer solutions of Ferrara et al. (1999), which assumes that the dust in this phase is uniformly mixed with the stars in the disk, with a Milky Way extinction law. The parameters adopted in Baugh et al. (2005) and Lacey et al. (2011) are $f_{\text{cloud}} = 0.25$, $t_{\text{esc}} = 1 \text{ Myr}$, $M_{\text{cloud}} = 10^6 M_{\odot}$ and $r_{\text{cloud}} = 16 \text{ pc}$, motivated by those used in the radiative transfer code GRASIL (Silva et al. 1998), which calculates the reprocessing of stellar radiation by dust and predicts a SED that has been tested against observed SEDs.

The calculation of dust emission above gives a total dust luminosity, which we refer to as the IR luminosity in the rest of this thesis, unless otherwise stated.

2.9 Main Differences Between the Baugh et al. (2005) and Bower et al. (2006) Models

The main successes of the Bower et al. (2006) model are the reproduction of the observed break in the galaxy luminosity function (LF) at $z = 0$ in the b_J - and K -bands, the observationally inferred evolution of the stellar mass function up to $z \approx 5$, the bimodality in the colour-magnitude relation Bower et al. (2006) and the abundance and properties of extremely red galaxies (Gonzalez-Perez et al. 2009). The Baugh et al. (2005) model likewise matches the b_J - and K -band LFs at $z = 0$, but also the number counts and redshift distribution of sub-millimetre selected galaxies (see also González et al. 2011), the size-luminosity relation for disk galaxies (Almeida et al. 2007; González et al. 2009), the evolution of Ly α -emitters (Le Delliou et al. 2006; Orsi et al. 2008), counts, redshift distributions and LFs of galaxies selected in the mid- and far-IR (Lacey et al. 2008, 2010) and the Lyman-break galaxy LF at redshifts $z = 3 - 10$ (Lacey et al. 2011).

We refer the reader to the original papers for full details of the Baugh et al. (2005) and Bower et al. (2006) models. Discussions of the differences between the models can be found in Almeida et al. (2007), González et al. (2009), Gonzalez-Perez et al. (2009) and Lacey et al. (2011). Briefly, the main differences between the models are:

- The SF timescale in galactic disks. The Bower et al. (2006) model adopts a parametrization for the SF timescale which depends on the global dynamical timescale of the disk, whereas the Baugh et al. (2005) model adopts a timescale which depends only on the disk circular velocity (see Sect. 2.4.1). Consequently, high redshift galaxies in the Baugh et al. (2005) model have longer SF timescales than those in the Bower et al. (2006) model and are therefore more gas-rich. This leads to more SF activity in bursts in the Baugh et al. (2005) model compared to the Bower et al. (2006) model.
- The IMF is assumed to be universal in the Bower et al. (2006) model, while the Baugh et al. (2005) model assumes two IMFs, a top-heavy IMF during SBs and a Kennicutt IMF during quiescent SF in disks.
- The Bower et al. (2006) model reincorporates the cold gas reheated by SNe into the hot halo after 2 dynamical times (which is a model parameter), while the Baugh et al. (2005) model does it only after the DM halo doubles its mass.
- In order to reproduce the bright-end of the LF, the Baugh et al. (2005) model invokes SNe driven superwinds with a mass ejection rate proportional to the SFR, where the expelled material is not reincorporated into any subsequent halo in the DM merger tree. The Bow06 model includes AGN feedback to switch off the cooling flow in haloes where the central BH has an Eddington luminosity exceeding a multiple of the cooling luminosity.
- The Bower et al. (2006) model includes disk instabilities (e.g. Mo et al. 1998) as an extra mechanism to trigger bursts of SF and to make spheroids, and hence to build BH mass (Fanidakis et al. 2011).

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