Galactic porosity and a star formation threshold for the escape of ionising radiation from galaxies

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ABSTRACT

The spatial distribution of star formation within galaxies strongly affects the resulting feedback processes. Previous work has considered the case of a single, concentrated nuclear starburst, and also that of distributed single supernovae (SNe). Here, we consider ISM structuring by SNe originating in spatially distributed clusters having a cluster membership spectrum given by the observed \( \text{H}_\text{II} \) region luminosity function. We show that in this case, the volume of \( \text{H}_\text{I} \) cleared per SN is considerably greater than in either of the two cases considered hitherto.

We derive a simple relationship between the “porosity” of the ISM and the star formation rate (SFR), and deduce a critical SFR\(_{\text{crit}}\), at which the ISM porosity is unity. This critical value describes the case in which the SN mechanical energy output over a timescale \( t_\text{e} \) is comparable with the ISM “thermal” energy contained in random motions; \( t_\text{e} \) is the duration of SN mechanical input per superbubble. This condition also defines a critical gas consumption timescale \( t_\text{exh} \), which for a Salpeter IMF and random velocities of \( \approx 10 \text{ km s}^{-1} \) is roughly \( 10^{10} \) years.

We draw a link between porosity and the escape of ionising radiation from galaxies, arguing that high escape fractions are expected if SFR > SFR\(_{\text{crit}}\). The Lyman Break Galaxies, which are presumably subject to infall on a timescale < \( t_\text{exh} \), meet this criterion, as is consistent with the significant leakage of ionising photons inferred in these systems. We suggest the utility of this simple parameterisation of escape fraction in terms of SFR for semi-empirical models of galaxy formation and evolution and for modeling mechanical and chemical feedback effects.

Key words: stars: formation — ISM: structure — galaxies: evolution — galaxies: high-redshift — diffuse radiation — early universe

1 INTRODUCTION

Feedback from supernovae (SNe) is a major ingredient of most contemporary models for galaxy formation and evolution. One of the main motives for its inclusion is the need to reconcile the predictions of CDM cosmology with the observed galaxy luminosity function (e.g. Cole et al 1994, 2000; Efstathiou 2000): the overproduction of dwarf galaxies in CDM models can be alleviated if star formation is inefficient in low mass systems, and the explosive energy input from SNe provides an obvious mechanism for ejecting gas from the shallow potentials of dwarf galaxies. SNe also return metals to the ISM, and if this process is coupled with the strong outflows posited above, can also provide a mechanism for enriching the IGM (e.g., Dekel & Silk 1986; Madau, Ferrara and Rees 2001).

Another aspect of SN-driven feedback that has received rather less attention is its possible relation to the escape of ionising radiation from star forming galaxies. It is currently unclear whether stellar sources or quasars are mainly responsible either for the re-ionisation of the Universe at high redshift or for the present day ultraviolet background (Madau, Haardt and Rees 1999), the answer depending critically on the assumed fraction of Lyman continuum photons that are able to escape star forming galaxies (Giallongo et al 1997; Madau and Shull 1996; Bianchi et al 2001). The simplest parameterisation of this problem involves assuming a constant escape fraction for all galaxies, but there are obvious reasons for supposing that in reality the escape fraction should depend on galactic parameters. In particular, the escape fraction, which depends on the distribution of neutral hydrogen along the line of sight, is likely to be strongly affected by the the re-structuring of the ISM effected by SN explosions. At a qualitative level, it would seem evident that higher escape fractions should be expected in systems with a higher star formation rate, since the disintegration of in-
interacting SN-driven bubbles can in principle open up lines of sight through which Lyman continuum photons can leak. Some observational support for the notion is provided by the recent detection of Lyman continuum emission in the composite spectra of Lyman Break Galaxies (Steidel et al. 2001), which include systems undergoing vigorous star formation.

To date, however, calculations of escape fractions in star forming galaxies do not exhibit a strong dependence of escape fraction on star formation rate (SFR); in the case of photoionisation calculations in a smoothly stratified ISM (Dove and Shull 1994; Ricotti and Shull 2000; Wood and Loeb 2000) the derived low escape fractions are not strongly dependent on the SFR, provided this exceeds the threshold value at which the resulting H ii regions cease to be ionisation bounded. Recent calculations by Ciardi et al. (2001), demonstrate an even weaker dependence of escape fraction on SFR in the case of an inhomogeneous, fractal ISM. In all these calculations, however, the assumed ISM structure is independent of star formation activity. The effects of mechanical feedback on the escape of ionising radiation have so far only been considered in the case of a coeval burst of star formation, where the source of ionising radiation and SN energy originate in the same region (Tenorio-Tagle et al. 1999; Dove, Shull and Ferrara 1999): here the temporary trapping of the ionisation front in the wall of the SN-driven bubble and the steep temporal decline of the ionising radiation from the burst combine to also produce a low escape fraction.

In this paper, we consider the case where the photons from each OB association impact on an ISM that has been structured by SN-blown superbubbles, reflecting its star formation history over the last $10^{7} - 10^{8}$ years. We thus draw a link between the porosity of the ISM, i.e., the fraction of the ISM that is devoid of H i due to the expansion of SN-driven bubbles, and the resulting escape fraction of ionising radiation. In order to quantify this link in more detail, one requires both 3D hydrodynamic calculations, which model the bubble evolution and the interaction of adjoining bubbles, and radiative transfer calculations, which calculate the escape of ionising radiation from the ISM. As we show in Section 2.1, this model implies that the escape fraction should rise steeply as the porosity of the ISM approaches unity, set up a model of the ISM which allows the porosity to be readily calculated as a function of SFR and galactic parameters.

In this work, we focus on the volume, $V_{\text{in}}$, of the ISM that is cleared of neutral hydrogen per unit SN explosion. This value depends strongly on the spatial distribution and clustering properties of the SN progenitors. Since superbubbles expand to the point that they are in rough pressure equilibrium with the ISM, it follows that an upper limit to this quantity is $V_{\text{max}}$, the volume of ISM originally containing a thermal energy equal to the SN energy ($\sim 10^{51}$ ergs). Note that in this work, we consider “thermal energy” to refer to both macroscopic and microscopic random motions in the ISM.

To date, most previous analyses have made either one of two extreme assumptions regarding the distribution of SN progenitors: either they are distributed singly throughout the galaxy (Larson 1974; McKee and Ostriker 1977; Dekel and Silk 1986; Efstathiou 2000) or else, as in more recent studies (De Young & Heckman 1994; Suchkov et al. 1994; Mac Low and Ferrara 1999; Strickland & Stevens 2000) they are concentrated in a single coeval, cospatial burst of star formation. Each of these assumptions however predicts a volume cleared per SN that is much less than $V_{\text{max}}$, though for different reasons in the two cases. In the case of single SNe, the limiting factor is the cooling of the shocked ISM (Cox 1972; Chevalier 1974; Goodwin et al. 2002), following which the bubble expands as a pressure driven snow plough. Due to these radiative losses, the final bubble encloses a volume of ISM that is a few per cent of $V_{\text{max}}$ (Ciotti et al. 1988). In the case of clustered SN progenitors, the effect of multiple SNe may be modeled as a continuous input of mechanical energy, analogous to a stellar wind (McCray & Kafatos 1987; Mac Low & McCray 1988), and in this case it is found that cooling is of marginal importance. However, in the case of a luminous starburst in a disc galaxy, the superbubble blows out when its size is between one and two disc scale heights. The bubble interior is consequently depressurised by the loss of hot gas normal to the disc plane, and again the resulting cavity in the ISM implies a volume cleared per SN that is much less than $V_{\text{max}}$.

In this paper we examine the case in which SNe are distributed according to the observed distribution of OB stars in galaxies. Specifically, we consider spatially distributed OB associations and superclusters whose membership numbers are inferred from the observed luminosity function of H ii regions and OB associations (Oey and Clarke 1998; McKee and Williams 1997). The OB association membership function is such that the number of associations having numbers of stars between $N_{\text{star}}$ and $N_{\text{star}} + dN_{\text{star}}$ is $\propto N_{\text{star}}^{-2}$. This distribution is similar in functional form to the observed mass distribution of clumps within molecular clouds and the membership number function for all types of stellar clusters (Blitz 1991; Elmegreen and Clemens 1985; Harris and Pudritz 1994; Elmegreen &Efremov 1997; Meurer et al. 1995). In a previous paper (Oey and Clarke 1997), we quantified the distribution of H i hole sizes predicted by such a model and found it to be in excellent agreement with the observed distribution of H i holes in the Magellanic Clouds (Oey & Clarke 1997; Kim et al. 1999). This empirical success encourages us to assume that this scale-free distribution of OB association richness is a universal characteristic of the ISM on all scales and in all environments. With such a prescription we can compute the escape fraction of the ISM that is cleared of H i for a given SFR (Oey et al. 2001), and also follow the evolution of this quantity during an episode of star formation. As we show in Section 2.1, this model implies that the volume of ISM swept up per SN is considerably larger than in either of the two limits that have been considered to date, and may be a significant fraction of $V_{\text{max}}$.

Our analysis expands on the premise introduced by Oey et al. (2001), of a critical SFR$_{\text{crit}}$, such that lower rates produce a volume filling factor of holes that is considerably less than unity. Under these circumstances, we surmise that the escape fraction of ionising radiation will be low, as found in photoionisation calculations based on a smoothly stratified ISM. If the star formation rate exceeds this value, the ISM becomes filled with hot bubbles and we speculate that the escape fraction from the ISM may rise considerably at this point, as the widespread merging of bubbles leads to the break up of shell walls through a variety of instabilities. Disc
systems may be able to continue to produce stars at such a rate, but in spheroidal systems, such as molecular clouds or proto-globular clusters, this seems unlikely, as the energy input into the gas from SNe at this point is comparable with the self-gravitational binding energy of the system. We investigate, in a crude analysis, how the finite time required to clear the star forming region of H I affects the number of ionising photons that can escape from the system, taking into account the rapid temporal decline of the ionising luminosity produced by a stellar population. Our approach is thus especially useful in providing estimates of escape fractions and star formation efficiencies for regions that may be below the resolution limit for numerical simulations of galaxies.

The structure of the paper is as follows. In Section 2 we set out the model for the growth of superbubbles and derive an expression for the porosity of the galaxy as a function of time, SFR, and ISM parameters, including an analysis of how the results are modified in disc systems, and establish the existence for a critical star formation threshold. In Section 3 we assess the consequences of the model for the star formation efficiency and escape of ionising photons from galaxies. In Section 4 we apply the results of the foregoing sections to a variety of star forming regions, including Lyman break galaxies, starbursts and giant molecular clouds. Section 5 summarises our conclusions.

2 POROSITY RELATED TO STAR FORMATION: AN ANALYTICAL APPROACH

Oey & Clarke (1997; hereafter OC97) estimate galactic porosity as the volume of superbubbles generated by OB associations relative to the simple geometric volume of the host galaxy. Here, we examine the porosity in more detail and relate it specifically to the ISM thermal energy and mass.

2.1 The volume of hot gas generated by star formation: steady state

We take the mechanical luminosity function (MLF) for the SN energies of the OB associations to be,

\[ \phi(L) = AL^{-2} \]  

(1)

where \( \phi(L) \) is the fraction of clusters with mechanical luminosity in the range \( L \) to \( L + dL \). The power-law slope of \(-2\) is empirically well-determined from the H II region luminosity function and stellar cluster mass function, as described above. Such a distribution implies that equal decades in cluster luminosity contribute equally to the total integrated mechanical luminosity, or, equivalently, SFR, of the galaxy. Thus the total SFR is dominated neither by very populous nor very sparse clusters. We furthermore assume that this luminosity function extends over a range of luminosities corresponding to a supernova membership number in the range \( N_{\text{min}} (\geq 1) \) to \( N_{\text{max}} \).

Following OC97, the lifetime of all superbubbles is assumed to be roughly equal to the main-sequence lifetime of the lowest mass SN progenitor, \( t_e \sim 40 \text{ Myr} \) for Population I stars. Therefore, if constant star-forming conditions are sustained for periods in excess of \( t_e \), the differential super-bubble size distribution attains a steady state, as derived by OC97:

\[ N(R) = A\psi L^{-1}e^{-1} \left( \frac{R}{R_e} \right)^{-3} \left[ 2(t_e + t_s) - \frac{3}{4} t_e \left( \frac{R}{R_e} \right) \right] , \quad R \leq R_e \]  

(2)

and

\[ N(R) = 5A\psi L^{-1}e^{-1} \left( \frac{R}{R_e} \right)^{-6} \left[ \frac{t_e}{4} + t_s \right] , \quad R > R_e \]  

(3)

where \( \psi \) is the creation rate of the superbubbles, \( L_e \) is the luminosity of a bubble that comes into pressure equilibrium with the ambient medium after time \( t_e \) and \( R_e \) is the corresponding radius of such a bubble at that time. It is assumed that the growth of bubbles with \( L < L_e \) stall by pressure confinement at the point that they come into pressure balance with the ambient medium. After \( t_e \), the SN energy stops, and the object is presumed to survive at constant radius for another increment of time \( t_s \).

For this steady-state size distribution and constant MLF, the total volume of superbubbles depends only on \( \psi \), or equivalently SFR, and the interstellar conditions that determine \( R_e \). The total volume of the superbubbles in a steady state is

\[ V_{\text{tot,ss}} = \int_{R_{\text{min}}}^{R_{\text{max}}} \frac{4}{3\pi} R^3 N(R) \, dR \]  

(4)

where \( R_{\text{min}} \) is the stall radius of a bubble containing \( N_{\text{min}} \) supernovae and \( R_{\text{max}} \) is the size of a bubble containing \( N_{\text{max}} \) supernovae at time \( t_e \). Thus integrating equations 2 and 3 gives a total volume,

\[ V_{\text{tot,ss}} \approx 3\pi A\psi L^{-1}e^{-1} \left( t_e + 2t_s \right) R^3 \]  

(5)

Equation 1 is a probability distribution, so its integral is unity, and therefore \( A \approx L_{\text{min}} \), yielding,

\[ V_{\text{tot,ss}} \approx 3\pi N_{\text{tot}} \left( \frac{L_{\text{min}}}{L_e} \right) R^3 \]  

(6)

where \( N_{\text{tot}} \) is the total number of superbubbles in the steady state.

The total number of supernovae contained in this population of bubbles is (from equation 1)

\[ N_{\text{sn}} \approx N_{\text{tot}} N_{\text{min}} \ln \left( \frac{N_{\text{max}}}{N_{\text{min}}} \right) \]  

(7)

so that the mean volume of ISM cleared per supernova, \( V_{\text{sn}} \) is

\[ V_{\text{sn}} \approx \frac{3\pi}{\ln \left( \frac{N_{\text{max}}}{N_{\text{min}}} \right) N_e} R^3 \]  

(8)

where we have used the fact that \( L \propto N \), and we define \( N_e \) as the number of SNe corresponding to mechanical luminosity \( L_e \). We will use these expressions for SN-cleared volume in deriving the interstellar porosity below.

Equation 3 shows that \( R_e \) dominates \( V_{\text{sn}} \). Note that since \( R_e \) is the radius at which a bubble containing \( N_e \) supernovae comes into pressure balance with the ISM, one can roughly equate the thermal energy of the ISM contained within \( R_e \) with the total energy input from \( N_e \) supernovae:

\[ N_e E_{\text{sn}} \approx \frac{4\pi}{3} R^3 u \]  

(9)
where $E_{\text{sn}} \sim 10^{51}$ erg is the SN energy and $u$ is the thermal energy density in the ISM. We thus deduce that $V_{\text{sn}}$ is within a factor of order unity of $V_{\text{max}}$:

$$V_{\text{max}} \sim \frac{E_{\text{sn}}}{u} \ .$$

(10)

which, as discussed in §1, is the mean volume per supernova for the adiabatic evolution of individual SNe.

The finding that $V_{\text{sn}} \approx V_{\text{max}}$ contrasts with the two scenarios considered by previous authors, namely, either distributed individual SNe, or else all SNe concentrated in a single bubble. The difference may readily be traced to the fact that when one considers a realistic spectrum of cluster richness (i.e. a MLF) there is an important volumetric contribution from bubbles with $L \approx L_c$. Such bubbles, which stall after a time $t_c$, remain in the adiabatic expansion phase over their entire SN-producing lifetime and thus represent optimal coupling between the supernova energy and clearing of the ISM. Note also that $V_{\text{sn}}$ is insensitive to any upper cut-off in the richness of OB associations, provided that the MLF extends well beyond $L_c$, since the volumetric contribution of bubbles with $L \gg L_c$ is small (equation [3]).

### 2.2 Non-steady star formation

The above analysis may readily be modified to model an episode of star formation that proceeds at constant rate over a timescale $t < t_c$. Such a situation is only relevant to star forming systems that can switch on their star formation on timescales $\ll t_c$ and thus applies to compact systems with short dynamical timescales, such as molecular clouds and globular clusters, as discussed in §4.1.

At time $t(t < t_c)$, the transition from the size distribution given by equation [3] to that of equation [5] occurs at radius $R_t$, instead of $R_c$, where $R_t$ is the radius of a bubble that just stalls at time $t$. Consequently, the total volume of superbubbles after time $t$ is given by:

$$V_{\text{tot,ns}}(t) = 3\pi N_{\text{tot}}(t) R_t^2.$$ 

(11)

$N_{\text{tot}}(t)$, the total number of superbubbles produced in time $t$, is proportional to $t$, whereas one may readily show (OC97) that $R_t \propto t$. Consequently, the volume of hot gas created varies quadratically with time, so that one may write

$$V_{\text{tot,ns}}(t) = V_{\text{tot,ns}} \left( \frac{t}{t_c} \right)^2 .$$

(12)

### 2.3 Effect of cooling and finite scale of ISM

The above analysis is appropriate to an infinite ISM where the bubble evolution remains adiabatic until it comes into pressure equilibrium with the ISM.

We verify the approximate validity of the adiabatic assumption by comparison of the bubble stall radius with the cooling radius given by Mac Low and McCray (1988). The former may be written (e.g. see OC97) in the form:

$$R_f = 300 \text{ pc} \ P_{\text{MW}}^{1/2} \ n_{\text{MW}}^{-3/4} .$$

(13)

Note that throughout this paper we use the term ‘thermal’ energy to denote energy in random motions in the ISM, whether this is dominated by bulk cloud motions or by motions at a molecular (thermal) level.

where $L_{38}$ is the luminosity normalised to $10^{38}$ erg s$^{-1}$ (equivalent to an OB association with $\sim 100$ SN progenitors). $P_{\text{MW}}$ and $n_{\text{MW}}$ are respectively the pressure and number density of the ISM normalised to their values in the Milky Way ($3 \times 10^{-12}$ dyne cm$^{-2}$ and 0.5 cm$^{-3}$). The corresponding expression for the cooling radius of freely expanding bubbles, using a cooling function appropriate to solar metallicity gas, is (Mac Low and McCray 1988):

$$R_c \approx 540 \text{ pc} \ L_{38}^{4/11} n_{\text{MW}}^{-7/11} .$$

(14)

These expressions imply that even in the case of solar metallicity gas, cooling is of marginal importance before the point is reached where the counter-pressure of the ISM is significant in slowing the expansion; for lower metallicity systems, cooling would be of still less importance. This hence justifies our treatment of the evolution prior to stalling as approximately adiabatic.

We now consider how the above analysis is modified when one takes into account the finite extent of the ISM. In general, bubbles evolve as described above, provided their sizes remain less than the density scale length of the ISM. Once they grow to larger radii, their evolution is modified by the ambient density gradient: in particular, a decreasing gradient causes the bubble expansion to accelerate due to the decreasing inertia of the newly swept up material. In disc-like density distributions, for example, a number of authors have performed hydrodynamical simulations of bubbles that demonstrate that bubbles ‘break out’ of the disc when they grow to a height between one and two disc scale heights (e.g., Mac Low and McCray 1988). At this point, the contents of the hot bubble interior are vented normal to the disc plane. Thereafter, the bubble evolution in the disc plane is no longer adiabatically driven, but evolves in a momentum-conserving fashion. We now calculate how the volume of ISM occupied by bubbles is reduced if one takes this into account.

It is convenient to divide the bubble population into low luminosity objects having $L < L_H$, which stall at sizes less than the disk scale height $H$, and higher luminosity objects that break out of the disc. From integration of equation [3], it can be seen that the total volume of bubbles contained in objects with radius less than $R$ is roughly proportional to $R$, and the total volume contained in bubbles that never break out of the disc is a factor $\sim H/R_c$ times the total volume of bubbles that would be created in an infinite medium for a given SFR.

We now estimate the total sudden swept out by bubbles with $L > L_H$. Such bubbles evolve adiabatically prior to breakout and hence the kinetic energy of the bubbles walls is proportional to the number of supernovae that have gone off at that point. Since bubbles attain a fixed size scale on a timescale $t_H$ that scales as $L^{-1/3}$ (OC97), the kinetic energy of bubbles at breakout scales as $L \times t_H \propto L^{2/3}$. All bubbles with $L > L_H$ break out when the volume of ISM swept up is $\sim H^3$, so that the mass of ISM swept up at breakout is independent of $L$. Hence the moment of ISM at breakout scales simply as the square root of the energy, i.e. as $L^{1/3}$. Thereafter, the bubbles evolve in an approximately momentum-conserving fashion and then stall when their expansion velocities become of order the thermal speed in the ISM. Thus, it follows that the final volume of the bubble is proportional to the momentum at breakout, and hence also
scales as $L^{1/3}$. We can obtain the normalisation by noting that objects that just stall at size scale $H$ are by definition not going to undergo further momentum-conserving expansion, because their velocity has already declined to thermal values.

Thus we find that the final volume of a bubble of size $L > L_H$ is given by $H^3 (L/L_H)^{3/2}$ (see also Koo & McKee 1992), as compared with the final bubble volume in an infinite medium which can be written as $H^3 (L/L_H)^{3/2}$ (OC97). By integrating each of these expressions over the MLF (equation 9), we find that bubbles that have broken out contribute a total volume that is a factor $\approx H/R_e$ times the total volume filled in the case of an infinite medium. [Note the bubbles with $L > L_H$ then contribute a volume fraction that exceeds the above estimate by only a logarithmic factor ($\ln L_H^2$). The effect of continued SN driving is thus not expected to be large, and we therefore do not consider it further for the purpose of the rough estimates considered here.]

Thus adding together the total contributions from bubbles that do and do not break out, and taking $R_{\text{max}} \approx R_e$, we find that the volume of bubbles produced is reduced by a factor

$$f_d = 2H/R_e \quad (15)$$

In forthcoming sections, we shall apply this correction factor where necessary in order to reduce the volume of bubbles produced per unit SFR in disc galaxies.

2.4 Calculation of galactic porosity

In order to compute the porosity of the ISM, it is necessary to divide the volume of hot gas produced by star formation by the effective volume of the star forming system, $V$. Thus from equations 8 and 9 the steady state porosity can be written

$$Q_{ss} \simeq \frac{f_d V_{\text{tot,ss}}}{V} \simeq \frac{9}{4} \frac{f_d N_{\text{tot}} N_{\text{min}} E_{\text{sn}}}{uV}, \quad (16)$$

where $f_d$ is the factor (equation 13) that takes rough account of the reduction in galactic porosity in the case of disc systems. If the mean mass of stars produced per bubble is $m_*$, then $N_{\text{tot}}$ is related to the star formation rate by:

$$N_{\text{tot}} = \frac{\text{SFR}}{m_*} t_e, \quad (17)$$

whilst the product $uV$ is, by definition, the total thermal energy contained in the ISM of the system, $E_{\text{ISM}}$:

$$uV = E_{\text{ISM}} = \frac{1}{2} M_{\text{ISM}} \bar{v}^2, \quad (18)$$

where $M_{\text{ISM}}$ is the total mass in the ISM and $\bar{v}$ is the ‘thermal’ velocity dispersion. Thus 14 becomes

$$Q_{ss} \simeq \frac{9}{2} \frac{f_d N_{\text{min}} \text{SFR} t_e E_{\text{sn}}}{m_* M_{\text{ISM}} \bar{v}^2}. \quad (19)$$

For a Salpeter IMF and $N_{\text{min}} = 1$, the mean mass of stars per bubble can be written $m_* \approx 150 \ln(N_{\text{max}}) M_{\odot}$ and is thus weakly (logarithmically) sensitive to any upper cutoff in the MLF. Here we adopt $N_{\text{max}} \sim 7000$, which corresponds to the largest OB associations in the Milky Way (McKee and Williams 1997), and which is, incidentally about twice $N_e$ for Milky Way ISM parameters (OC97). In this case the mean number of supernovae per bubble is $\simeq 9$ and $m_* \simeq 1350 M_{\odot}$. (We note that if $N_{\text{max}}$ was an order of magnitude greater than this, $m_*$ would only increase by 25%). Taking $E_{\text{sn}} \sim 10^{51}$ ergs, we obtain:

$$Q_{ss} \simeq \frac{7 f_d \text{SFR}_{\odot}}{M_{\text{ISM},10} \bar{v}_0^2}, \quad (20)$$

where $\text{SFR}_{\odot}$ is the star formation rate in solar masses per year, $M_{\text{ISM},10}$ is the mass of the ISM in units of $10^{10} M_{\odot}$ and $\bar{v}_0$ is the thermal velocity of the ISM normalised to 10 km s$^{-1}$. In a system where star formation has been ongoing for a time $t < t_e$, the porosity is given by (equation 12):

$$Q(t) = Q_{ss} \left(\frac{t}{t_e}\right)^2, \quad (21)$$

Equation 21 implies that there is a critical star formation rate, $\text{SFR}_{\text{crit}}$, such that the porosity of the ISM is unity, i.e.

$$\text{SFR}_{\text{crit}} = 0.15 \left(\frac{M_{\text{ISM},10} \bar{v}_0^2}{f_d}\right) M_{\odot}\text{yr}^{-1}. \quad (22)$$

We stress that $\text{SFR}_{\text{crit}}$ is the SFR such that the energy output from SNe, over a timescale $t_e$, is comparable with the energy of the ISM contained in random motions. The normalisation of equation 22 thus depends only on the assumed IMF and the stellar astrophysics contained in the value of $t_e$ and the energy delivered per SN. (We note, however, that in reality equation 22 should be regarded as a very rough guide, since its derivation suffers from the obvious over-simplification that results from approximating the ISM of a galaxy as a smooth homogeneous entity characterised by a single set of physical parameters. In practice, we will find equation 22 useful below in dividing highly porous regimes from the marginal case and from situations where the porosity is very low).

If $\text{SFR} < \text{SFR}_{\text{crit}}$, then such a SFR can be sustained indefinitely, provided the gas supply is large; star formation can proceed at such a rate over timescales $\gg t_e$, with the porosity attaining a steady state value of $Q_e < 1$.

If $\text{SFR} > \text{SFR}_{\text{crit}}$, then the system attains unit porosity after a time $t_Q$:

$$t_Q = t_e \left(\frac{\text{SFR}_{\text{crit}}}{\text{SFR}}\right)^{1/2}. \quad (23)$$

We discuss below the consequences of achieving unit porosity, but first note that the maximum rate of star formation achievable in a star forming system is

$$\text{SFR}_{\text{dyn}} \sim \frac{M_{\text{ISM}}}{t_{\text{dyn}}}, \quad (24)$$

where $t_{\text{dyn}}$ is the dynamical timescale of the star forming region.
3.1 Star formation efficiency

We have shown that the porosity of a star forming system becomes of order unity at the point that the input of mechanical energy into the ISM (over time $t_e$, or the duration of the burst, whichever is the shorter) is comparable with the thermal energy content of the ISM, where we take ‘thermal’ to denote random ISM motions. The critical SFR that must be sustained over a timescale $t_e$ in order to attain unit porosity is given by $SFR_{crit}$ (equation 2).

For a bound spheroidal system, the thermal energy content of the ISM is always of order its gravitational binding energy, whether the gravitational potential derives from the gas itself or is a background potential of dark matter and/or stars. Consequently, when the porosity attains a value $\sim 1$, the energy input into the ISM is comparable with its gravitational binding energy. As a result, one would not expect spheroidal systems to be able to sustain star formation rates much in excess of $SFR_{crit}$ over timescales $> t_e$.

In the case of compact systems with dynamical timescale $< t_e$, it is however possible for the SFR to exceed this limit temporarily. If, in this case, we consider the star formation event to be self-terminated after time $t_Q$ (equation 23), when the volume filling factor of superbubbles reaches unity, we can use equations (19) and (23) to derive the fraction of gas converted into stars during the event as:

$$\epsilon = \frac{2m_e v^2}{9E_{sn}} \left( \frac{SFR}{SFR_{crit}} \right)^{1/2}.$$  \hfill (25)

so that

$$\epsilon = 6 \times 10^{-4} v_{10}^2 \left( \frac{SFR}{SFR_{crit}} \right)^{1/2}.$$  \hfill (26)

The maximum fraction of the ISM that can be turned into stars increases with the square root of the SFR, and is thus limited by the upper, dynamical, limit to the SFR implied by equation 2 to the value:

$$\epsilon_{max} = \left( \frac{2m_e v^2}{9E_{sn}} \right)^{1/2} \left( \frac{t_{dy}n}{t_e} \right)^{-1/2}.$$  \hfill (27)

from which

$$\epsilon_{max} = 0.02 v_{10} \left( \frac{t_{dy}n}{t_e} \right)^{-1/2}.$$  \hfill (28)

In a disc system, by contrast, the thermal energy content of the ISM is $\ll$ its gravitational binding energy. Consideration of hydrostatic equilibrium normal to the disc plane demonstrates that the ratio of energy in random motions to gravitational binding energy is of order $(H/R)$ if the vertical gravity mainly derives from the disc’s local self-gravity, or $(H/R)^2$ if it instead derives from the vertical component of the gravity of a central mass concentration. Thus, star formation rates in excess of $SFR_{crit}$ do not imply the wholesale unbinding of the ISM and may not be ruled out on these grounds.

Whether or not $SFR_{crit}$ represents a maximum to the star formation rate in discs systems, or else a point of transition to star formation in a highly porous state, depends on conditions in the cool gas component once $Q \sim 1$ (i.e., equivalently, whether feedback operates positively or negatively on the cool gas). Several pieces of evidence suggest that star formation may well continue in this state. We will see below (Section 4.3) that some systems, notably Lyman Break Galaxies, apparently sustain star formation rates well in excess of $SFR_{crit}$ over prolonged periods ($10^8 - 10^9$ years; Shapley et al. 2001). A more local example is provided by the LMC. Although the porosity of this system is around unity (Oey et al. 2001), continuous vigorous star formation has been ongoing in the LMC disk for at least $10^8$ year, and possibly up to 15 Gyr (e.g., Smeeke-Hane et al. 2002; Dolphin 2000). Inspection of the LMC reveals how this situation is achieved: although the bulk of the system volume is filled with hot gas, chiefly in the halo, the bulk of the mass is in the cool component in the disc plane, where a high star-formation rate is maintained. This system shows little evidence for negative feedback effects on star formation, but is well-known to provide examples where star formation appears to be actively triggered in the cool gas constituting bubble walls (e.g., Yamaguchi et al. 2001; Oey & Massey 1995; Walborn & Parker 1992). The specific example of the supernova shell LMC-4, which is the largest and most studied case of LMC triggered star formation (e.g., Dopita et al. 1985; Braun et al. 1997; Olsen et al. 2001) clearly shows a massive ring of H I and star formation 1.4 kpc in diameter surrounding a large complex of young blue stars. However, the morphology is clearly ring-like, rather than shell-like, suggesting that mechanical feedback on these large scales does not remove the majority of shell gas from the low galactic latitudes, and does promote continued star formation. In what follows, therefore, we assume that in disc systems star formation can in principle continue in the cool component at rates in excess of $SFR_{crit}$.

We note that the characteristic gas exhaustion timescale for a system in a marginally porous state is given by:

$$t_{exh} = \frac{M_{ISM}}{SFR_{crit}} = 7 \times 10^{19} \frac{f_d}{v_{10}} \frac{d}{R} \text{ years},$$  \hfill (29)

where the value of $t_{exh}$ depends on the same assumptions about stellar astrophysics and IMF as detailed for $SFR_{crit}$ (equation 2).

3.2 Implications for the escape of ionising radiation

We have here presented a model of the ISM structured by SN explosions located in spatially distributed clusters, a model that has been successfully tested in the case of nearby galaxies. Our discussion of ionising photon escape from such a medium is necessarily more speculative, pending detailed hydrodynamic and photoionisation calculations. Here we explore the consequences of such a model by the following crude parameterisation of ionising photon escape: we assume that when the porosity of the ISM is $< 1$, no ionising photons can escape and that when the porosity is high ($> 1$) all ionising photons can escape.

It is easy to see why these assumptions are wrong in detail. For example, pure photoionisation codes of disc galaxies, i.e. calculations that assume a smoothly stratified initially neutral medium, suggest escape fractions of a few percent even in the absence of mechanical energy input from SNe. Likewise, it is well-established that populous clusters can create local chimneys in the ISM, thereby launching galactic superwinds and it is reasonable to expect some pho-
ton leakage in this case (see, however, Tenorio-Tagle et al. 1999; Dove, Shull and Ferrara 1999) even when the global star formation rate is \( \lesssim \text{SFR}_{\text{crit}} \). It is also unlikely that the escape fraction is as high as unity even when the ISM is highly porous. Although most of the volume of the ISM is cleared of neutral material in this case, most of its mass is contained in neutral bubble walls. We here assume that a variety of hydrodynamical instabilities break up the bubble walls once the bubbles start to overlap strongly, thus opening up lines of sight through which ionising photons can escape the disc. In order to escape the galaxy, however, such photons also have to propagate through low density material in the halo without encountering significant opacity from neutral hydrogen. Detailed hydrodynamic/radiative transfer calculations are required, which model the input of ionising photons and mechanical energy into the halo from spatially dispersed, non-coeval star formation events in the disc, in order to assess whether the halo can be maintained in a state of sufficient transparency.

Despite the above caveats, we argue that this simple prescription captures an important dependence of the escape fraction of ionising radiation on SFR. Systems maintaining a steady state star formation rate on timescales greater than \( t_e \) can exist in two states: if \( \text{SFR} < \text{SFR}_{\text{crit}} \) the escape fraction is low and star formation can in principle proceed at such a rate until all the gas is exhausted. On the other hand, disc systems which are re-supplied on a timescale less than \( t_{\text{evap}} \) (equation 29) may sustain SFRs in excess of \( \text{SFR}_{\text{crit}} \), in which case the escape fraction would be high.

For star-forming systems in which the dynamical timescale is less than \( t_e \), the SFR can vary on a timescale less than \( t_e \), offering the possibility that the SFR may temporarily exceed \( \text{SFR}_{\text{crit}} \). During such a star formation episode, the porosity of the system rises, attaining unity at time \( t_Q \). We have argued that in spheroidal systems, star formation is self-limited at this point. Ionising photons from the population created prior to this can then escape the immediate vicinity relatively easily; the above crude model posits escape with unit probability. Given an IMF and relationships between ionising luminosity, mass and lifetime, one may readily calculate an upper limit to the number of ionising photons escaping the region. Specifically, if the number of ionising photons emitted by the population prior to time \( t \) is \( N_{\text{ion}}(t) \), then this upper limit is given by:

\[
f_{\text{esc}} = 1 - \frac{N_{\text{ion}}(t_Q)}{N_{\text{ion}}(\infty)}. \tag{30}
\]

Note that, whereas escape fractions are conventionally defined in terms of rates, in the case of a finite episode, it makes sense to define the escape fraction in terms of numbers of ionising photons.

Figure 1 illustrates the dependence of \( f_{\text{esc}} \), as defined above, on the duration of a star formation burst \( (t_b) \) under the simple assumption that ionising photons escape only if emitted at times \( \geq t_e \). The two lines denote stars of Population I and III, with an assumed Salpeter IMF in both cases. Note that star formation is assumed to continue at constant rate until \( t_b \), unlike other recent studies of escape of ionising radiation from ageing populations (Dove, Shull and Ferrara 1999; Tenorio-Tagle et al. 1999) where all the star formation is concentrated in a burst at time \( t = 0 \). Stellar data for Population I stars is taken from Maeder 1990 and Díaz-Miller et al. 1998, whilst for Population III stars, models have kindly been supplied by Chris Tout in advance of publication. The curve for Population II stars would be almost indistinguishable from that for Population I, since the main dependence of ionising luminosity on metallicity occurs for stars of sufficiently low mass that they make a rather small contribution to the total ionising output of the cluster. The Population III curve is rather different, however, since lower mass stars are considerably hotter in this case and make a significantly larger contribution to the total ionising output than for the Population I case. Consequently, a higher fraction of the ionising photons can escape at late times in the Population III case. The effect, however, is not enormous: for bursts terminated after \( \sim 20 \text{ Myr} \) the escape fraction (equation 1) for Population III stars is \( \sim 25\% \) compared with a value that is roughly a factor of two lower for Population I stars.

4 APPLICATION TO STAR FORMING SYSTEMS

4.1 Compact systems

The basic building block of star formation at the present epoch is the Giant Molecular Cloud, and we here apply our simple model to assess the internal self-destruction of GMCs through the action of SNe and stellar winds (see Franco and Cox 1983 for an assessment of the effects of winds from low mass stars on the dispersal of molecular clouds). For typical parameters \( (M_{\text{ISM}} = 2 \times 10^5 M_\odot, v_1 \sim 0.2) \) it follows from equation 22 that \( \text{SFR}_{\text{crit}} \) is a tiny \( 10^{-7} M_\odot \text{ yr}^{-1} \), which is many orders of magnitude less than the observed SFR in GMCs. The dynamical timescale of GMCs is short (a few
pendent on stellar mass (Bond et al 1984, Fryer et al 2001).

For around 2 Myr until the explosion of the first supernova. As a result, significant feedback effects are delayed for around 2 Myr until the explosion of the first supernova. This factor may explain the high inferred star formation efficiency in proto-globular clusters (Murray and Lin 1989; Geyer and Burkert 2001) and the compact nature of globular clusters. More speculatively, we suggest that the population of ‘faint fuzzies’ (diffuse red clusters recently discovered in early type galaxies; Larsen and Brodie 2000; Larsen et al 2001) may owe their relatively distended nature and weak gravitational binding to the stronger winds that operate in clusters whose metallicity is at the high end of the globular cluster metallicity distribution.

In Population III systems, winds are estimated to be many orders of magnitude weaker than in Population I stars (Bromm et al 2001b), so that one may effectively ignore mechanical feedback from winds in these systems. In the compact haloes that are expected to host Population III stars, the dynamical timescale is sufficiently short to allow efficient star formation prior to the explosion of the first supernovae. Since Population III stars are likely to be very massive (Bromm et al 1999, 2001a; Abel et al 2000), the further evolution then depends on the details of the resultant mass spectrum, since the energy output (and existence) of supernovae in stars more massive than 100$M_\odot$ is highly dependent on stellar mass (Bond et al 1984, Fryer et al 2001).

4.2 Milky Way

For the ISM properties of the Milky Way ($n \sim 0.5$ cm$^{-3}$, $\bar{v}_{10} \sim 1$), the radius of a bubble stalling after $t_e$ is $R_e \sim 1300$ pc (OC97), so that given the disc scale height of $H \sim 100$ pc, the correction factor for disc systems ($f_d$; equation 13) is around 15%. This means that the critical SFR required to achieve unit porosity is boosted by about 7 relative to its value in an infinite medium, due to the loss of accelerative power in bubbles that break out of the disc. For an ISM mass of $\sim 10^{10}M_\odot$ in the Milky Way, the critical star formation rate (equation 23) is roughly a solar mass per year, that is, comparable with the observed rate in the Milky Way (McKee and Williams 1997; McKee 1989). As discussed above, we may use our model as a crude indication of escape fraction: ‘low’ or ‘high’ for SFRs that are much less than or much greater than the critical value. We would not however trust it in the transitional case where the SFR is close to critical. (See also the discussion in OC97 of the porosity of the Milky Way).

4.3 Lyman Break Galaxies

The application of this model to Lyman Break Galaxies is currently rather uncertain, given uncertainties about the gas masses and morphologies of these objects. However, on the assumption that these are disc systems ($\bar{v}_{10} \sim 1$) with gas masses comparable with their virial masses ($\sim 10^{10} M_\odot$; Pettini et al 2001) one obtains values of $\text{SFR}_{\text{crit}} \sim 1 M_\odot$ yr$^{-1}$. The SFRs inferred in Lyman Break Galaxies studied to date are comfortably greater than this ($\sim 10 - 100 M_\odot$ yr$^{-1}$; Pettini et al 2001) leading to the expectation that ionising radiation should escape rather easily from these systems. The discovery of Lyman continuum emission in the composite spectra of Lyman Break Galaxies (Steidel et al 2001) is consistent with this conclusion. The positive correlation between SFR and escape fraction that this model predicts awaits the measurement of Lyman continuum emission in individual Lyman break systems.

4.4 Starbursts at low z

The nuclei of nearby starburst galaxies provide the best studied examples of vigorous star formation activity in the local Universe; the inferred SFRs (up to $\sim 20 M_\odot$ yr$^{-1}$ kpc$^{-2}$ for an assumed Salpeter IMF; Lehnert and Heckman 1996; Meurer et al 1997) are greatly in excess of $\text{SFR}_{\text{crit}}$, leading to the expectation that the porosity of the ISM in these regions should be high. Note that this conclusion does not depend on the IMF, but purely on the relationship between the massive star content and ISM properties. In the absence of replenishment, therefore, one would expect a high fraction of the ionising photons to be able to escape the nuclei of such galaxies.

The situation of starburst nuclei, located at the bottom of the galactic potential well, however, means that such regions are likely to be subject to continued replenishment of gas from larger radius during the history of the starburst. The dynamical timescales in such regions are short ($\sim 10^7$ years) and indeed less than or comparable with $t_e$. Consequently, neutral material can flow into the region on.
timescales less than $t_\epsilon$ and the filling factor of regions devoid of H I may not approach unity even at the high star formation rates typical of starbursts. Currently the available observational evidence is that the escape fraction from starburst nuclei is indeed low (Heckman et al 2001; Leitherer et al 1995). We highlight here the contrast with the Lyman Break Galaxies (see above), where the more extended star formation regions do not permit re-supply on a timescale of $t_\epsilon$.

5 CONCLUSIONS

We have developed a model where the ISM porosity, i.e., the fractional volume devoid of HI, is regulated by SN explosions. In this model, the SN progenitors are located in spatially distributed OB associations, membership numbers being dictated by the observed OB association luminosity function. This model has previously been shown to provide a good fit to the observed size distribution of H I holes in nearby galaxies.

We find that such a realistic distribution of SN progenitors ensures that the clearing of the ISM is more effective, per unit star formation rate, than in either the case of distributed single SNe or the case where all SNe are concentrated in a single region. This is because, given the slope of the OB association LF, the porosity in our model is dominated by bubbles that come into pressure equilibrium with the ISM on a timescale that is similar to $t_\epsilon$, where $t_\epsilon$ is the maximum lifetime of a SN progenitor and hence the timescale over which associations inject mechanical energy into the ISM. Such superbubbles evolve quasi-adiabatically and thus most of the mechanical energy of their SNe is deposited in the ISM. In consequence, for the population of bubbles as a whole, the average volume cleared per SN is within a factor of order unity of its theoretical maximum (equation 14), although this is somewhat reduced in the case of disc galaxies (equation 23). This contrasts with the situation of single SNe, where cooling limits the volume cleared, and also single burst models, where clearing is limited by the breakout of the bubble from the galactic plane.

This model yields a simple relationship between the star formation rate and interstellar porosity. Following the arguments above, the critical star formation rate (SFR$_{crit}$) required to attain a porosity of order unity is just that at which the energy input from SNe, over a timescale $t_\epsilon \sim 40$ Myr, is comparable with the thermal energy content of the ISM. For a given kinetic temperature of the ISM defined by the level of random motions, this implies a simple relationship between the SFR$_{crit}$ and the mass of the ISM (equation 22), and hence a characteristic timescale for gas exhaustion, $t_{\text{exh}}$ (equation 23). For a Salpeter IMF and ISM velocity dispersion of around $10 \text{ km s}^{-1}$, this critical star formation timescale is roughly $10^{10}$ years.

If spheroidal galaxies form stars at SFR$_{crit}$, the energy input into the ISM over $t_\epsilon$ is comparable with the gravitationally binding energy of the ISM and one might expect wholesale expulsion of the ISM to ensue. Disc systems, by contrast, can remain in a highly porous state and still retain their ISM. Although in this case the volume fraction of H I is then small, the mass fraction is still large, so we assume that star formation can proceed in the shredded walls of interacting superbubbles.

We furthermore suggest that the porosity of the ISM has an impact on the escape of ionising photons from galaxies, since the disintegration of overlapping bubbles can create channels in the ISM through which ionising photons can escape. This postulate must be assessed through detailed photoionisation calculations in a medium structured by supernova explosions whose progenitor OB associations are appropriately distributed in luminosity and space. We note that the recent analysis by Elmegreen et al (2001) of the morphology of the neutral ISM in the LMC favours the filament/bubble structure that is characteristic of a supernova-structured ISM.

If we tentatively accept this postulate, we would thus expect high escape fractions in galaxies whose star formation rates exceed SFR$_{crit}$, as would appear to be the case in Lyman Break Galaxies. Sustained star formation at such rates however requires that gas is replenished on a timescale less than $t_{\text{exh}}$ (see above). At recent cosmic epochs, the timescale for gaseous infall into galaxies is long, so that one would not expect that galaxies in general should display the high SFRs required to maintain a highly porous ISM. This conclusion is consistent both with measurements of the HI hole size distributions in nearby galaxies and with the low leakage of ultraviolet photons from the Milky Way based on Ha measurements of the Magellanic Stream (Bland-Hawthorn and Maloney 1999) During the assembly of galaxies at high redshift, however, much shorter infall timescales are expected, and we suggest that it is the continued infall of material into Lyman Break Galaxies that allows them to sustain vigorous star formation levels with a high associated escape fraction. In systems where the infall timescale falls to values less than $t_\epsilon$, however, the situation reverses, since the continual replenishment of neutral material into the star forming region can prevent the porosity from ever attaining high values. We suggest that this is why local starburst nuclei, being compact regions at the bottom of the galactic potential and thus subject to gaseous inflows on a short timescale, have a low escape fraction despite their high rates of star formation per unit gas mass.

We also consider compact systems, with dynamical timescales $< t_\epsilon$, in which the SFR may temporarily exceed SFR$_{crit}$ and we have estimated the maximum number of Lyman continuum photons that might be expected to escape these systems. The key factor here is the efficacy of feedback from stellar winds prior to the explosion of the first SN, which depends critically on metallicity. In Giant Molecular Clouds with near solar metallicity, we find that winds provide a very efficient means of cloud dispersal; we estimate that the maximum fraction of the cloud mass that can be converted into stars prior to their dispersal is a few per cent, close to the observationally inferred value. This suggests that stellar winds may be at least as important as photoionisation as a negative feedback mechanism in Giant Molecular Clouds. In Population III systems, by contrast, the mechanical feedback from stellar winds is negligible and clearing of the ISM is delayed until the explosion of the first SN. Supernovae are not expected for progenitors more massive than $250 M_\odot$ however, so that an extremely top heavy IMF might result in inefficient clearing and a low escape fraction of ionising radiation.
Finally, we present these calculations as a first attempt to parameterise the relationship between escape fraction and SFR in star-forming systems and suggest the utility of such a prescription in semi-empirical models of galaxy formation and evolution. The critical star formation rate may also offer a useful means to parameterize mechanical and chemical feedback.

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