

On the destruction of star-forming clouds

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Accepted 2004 July 1. Received 2004 June 29; in original form 2004 April 2

ABSTRACT

Type II supernovae (SNe), probably the most important contributors to stellar feedback in galaxy formation, explode within the very dense star-forming clouds, where the injected energy is most easily radiated away. The efficiency of Type II SNe in injecting energy into the interstellar medium (ISM) and in reheating a fraction of the original star-forming cloud is estimated with the aid of a two-phase model for the ISM of the cloud. We argue that when SNe explode the star-forming cloud has already been partially destroyed by ionizing light and winds from massive stars. Supernova remnants (SNRs) will first cause the collapse of most of the cloud gas into cold fragments, until the diffuse hot phase has a low enough density to make further radiative losses negligible. This is completed in ~ 3 Myr, with a modest energy loss of ~ 5 per cent of the total budget. We compute that a fraction ranging from 5 to 30 per cent of the cloud is reheated to a high temperature (from 10^5 to 10^7 K); these numbers are very uncertain, as a result of the very complicated nature of the problem and the uncertain role of thermo-evaporation. Small star-forming clouds, less massive than $\sim 10^4 M_{\odot}$, will be destroyed by a single SN. In all cases, a high fraction of the energy from Type II SNe ($\gtrsim 80$ per cent for large clouds, smaller but still significant for small clouds) will be available for heating the ISM.

Key words: ISM: bubbles – ISM: kinematics and dynamics – galaxies: formation – galaxies: ISM.

1 INTRODUCTION

The formation of stars and galaxies, as well as the state of the interstellar medium (ISM), are regulated by the feedback processes related to the energy injection into the ISM itself by stars through winds, ultraviolet (UV) photons and supernova explosions. In particular, a satisfactory model of galaxy formation requires that a significant fraction of the energy released by massive stars and supernovae (SNe) is given to the ISM and eventually to the hot, virialized gas component pervading the dark matter haloes.

The greatest part of the stellar energy budget is provided by Type II SNe, associated with short-lived massive stars. The cosmological community often restricts to this feedback source alone, thus neglecting not only the contribution of UV and winds, which are produced by a subset of the stars that die as SNe and whose energy budget is less than the uncertainty in the energy of the single SNR, but also the contribution of Type Ia SNe, associated with less massive stars. In this way, energy is injected where young stars reside, i.e. in the star-forming regions, which are systematically the densest ISM regions in a galaxy. In this context, the energy of SNe, which propagates into the ISM through blast waves, is very easily radiated away, giving rise to a low efficiency of energy injection.

The computation of the energy lost by a supernova remnant (SNR) while it gets out of a star-forming cloud is not easy, owing to a number of complications. OB stars are highly clustered, both within the galaxy (they reside in the star-forming, molecular clouds) and within the star-forming cloud itself (they reside in associations). In this way, most SNe explode in the hot bubbles created by previous explosions, giving rise to superbubbles more than isolated SNRs. Besides, the star-forming clouds are highly inhomogeneous, magnetized and dominated by supersonic turbulence.

A further crucial point is that the first SNe explode from massive progenitor stars that have already preheated the surrounding ISM by UV light and winds. This process has been addressed by many authors, for instance McKee, van Buren & Lazareff (1984), McKee (1989), Franco, Shore & Tenorio-Tagle (1994), Williams & McKee (1997), Matzner (2002) and Tan & McKee (2004). Despite all of the uncertainties, some consensus is emerging on the fact that UV light and winds from massive stars are able both to sustain the observed level of turbulence in the star-forming clouds and to destroy them in a time of the order of 10 Myr (but see also Ballesteros-Paredes, Vasquez-Semadeni & Scalo 2000). As a result, the bulk of SNe explode when the cloud is already in an advanced state of destruction.

In a recent paper (Monaco 2004, hereafter Paper I) we proposed a model for feedback in galaxy formation in the presence of a multi-phase medium. In that model, the most difficult piece of astrophysics to address was the efficiency of feedback in reheating a fraction of

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the star-forming cloud to some high temperature, together with the amount of energy lost by SNe before completing the destruction of the star-forming cloud. The first two quantities (fraction and temperature of reheated matter) were left as free parameters, and the last one (energy loss) was assumed to be negligible.

In this paper we compute these quantities through a simple model for the explosion of SNe in a preheated star-forming cloud. The model assumes that SNe explode inside a cloud composed of a two-phase medium in pressure equilibrium, with a hot diffuse phase and a cold phase fragmented into clouds. Owing to the complexity of the problem, we are well aware that the model presented here is too naive either to represent the full complexity of the process or to give accurate predictions for the quantities involved. However, the results give insight on the physical processes in play and are informative enough at a qualitative level to constrain the order of magnitude of the quantities cited above; they can be used as a guide for future numerical simulations of the destruction of star-forming clouds.

The paper is organized as follows. Section 2 presents the assumed initial conditions of the cloud when SNe start to explode, the model for the two-phase ISM, the fate of SNRs propagating in the cloud, the mass and energy flows within the components, and the system of equations used. Section 3 presents the resulting predictions of the model. Section 4 discusses the case of small and dense star-forming clouds, where only a few SNe per cloud explode, and Section 5 gives the conclusions.

2 THE MODEL

2.1 The state of the cloud at the first SN explosions

Molecular clouds are dominated by supersonic turbulence (see e.g. Solomon et al. 1987). According to recent simulations (Mac Low et al. 1998; Ostriker, Gammie & Stone 1999; Mac Low 2002), supersonic turbulence in a compressible fluid decays over a few crossing times. This is true also in the case of magnetohydrodynamic (MHD) turbulence. Besides, star formation takes place on longer time-scales and with a low efficiency, so that to obtain in a turbulent cloud a significant fraction of mass in stars (i.e. efficiency of star formation), comparable to the observed value ranging from 1 to 10 per cent (see e.g. Carpenter 2000), it is necessary to sustain turbulence. Moreover, observations suggest that star formation should not last more than ~ 10 Myr (see e.g. Elmegreen 2002).

UV light and winds from massive stars are likely to be responsible for the destruction of the star-forming clouds. For instance, Matzner (2002) argued that the expanding H II regions are the most likely drivers of turbulence, and that the gradual photodissociation of H₂ and the expulsion of reheated material leads also to the destruction of the molecular cloud, self-limiting the efficiency of star formation to the observed value. Requiring an equilibrium between the turbulence driven by the expanding H II regions and that dissipated by the turbulent cascade, and taking into account the rate at which ‘blister’ H II regions heat the gas to a temperature in excess of 10^4 K and expel it, Matzner computed that a cloud will be destroyed in a time ranging from 10 to 30 Myr, the lower values being valid for the largest molecular clouds. The efficiency of star formation that resulted was ~ 10 per cent, nearly independent of cloud mass. Matzner’s arguments are strictly valid for clouds with dynamical times shorter than the mean ionizing lifetime of massive stars (for a Milky Way ISM this amounts to $M > 10^5 M_{\odot}$) and with escape velocities smaller than twice the ionized sound speed (> 10 km s⁻¹).

According to Matzner (2002), SNe do not contribute significantly to the destruction of the cloud. In fact, the first SNe explode ~ 3 Myr

after the formation of their progenitor stars and are indeed associated with the same OB stars that produce the H II regions. They are so massive that their remnants can go directly to the snowplough stage (see below) while still in the early free expansion stage; they end up being confined within the H II region, after having radiated away most of their energy. Their contribution to the momentum of the H II region is thus small. However, this argument is correct only for the first SN that explodes in each OB association. A second explosion within the same association would propagate into a rarefied hot bubble; in this case the blast would reach the ionization front before losing much energy. Moreover, many SNe come from smaller stars that explode later and are not necessarily associated with big H II regions. As a consequence, only the energy of the very first SNe will be completely lost; besides, energy injection by multiple SNe will become important later than 3 Myr, when the process of cloud destruction is already in an advanced state.

While the precise origin of turbulence in star-forming clouds is still to be demonstrated, the energetic input of OB stars is likely to have a dramatic role in the destruction of the molecular, star-forming clouds. We thus deem it realistic to assume that, when the first SNe explode, the cloud is composed of two phases: a hot diffuse one, heated up by H II regions, and a cold collapsed one, fragmented into cloudlets with a given mass spectrum. Pressure equilibrium between the two phases is assumed; this is justified by the finding of rough isobaricity in simulations of turbulent ISM (Kritsuk & Norman 2002; see Vazquez-Semadeni 2002 and Mac Low 2003 for reviews). The expanding SNRs act in shaping the ISM within the cloud as follows (Fig. 1): blasts in the adiabatic stage heat the diffuse phase, while in the snowplough stage (see below) they collapse it. Thermo-evaporation of cold clouds within the expanding blasts transfers mass from the collapsed to the diffuse phase. Radiative cooling transfers mass from the diffuse to the collapsed phase.

The initial conditions of the cloud are specified through its mass M_{cloud} and initial radius R_{cloud} . Paper I shows that these quantities are related to the state of the ISM outside the cloud; however, to keep the formalism simple, we avoid making this connection explicit. In any case we assume that the external ISM is two-phase as well, with densities of ‘cold’ and ‘hot’ phases n_c and n_h , respectively. Moreover, we assume for simplicity that the cloud is spherical. Following the discussion given above, a significant fraction of mass is put into

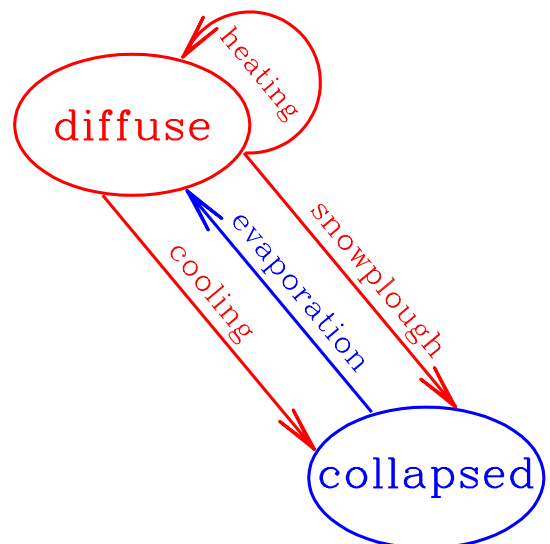


Figure 1. Mass flows in the model.

the diffuse phase; the temperature of the collapsed phase is kept fixed to 100 K as in Paper I. A fraction f_* of the cloud is assumed to be in stars at the beginning of the calculation, which coincides with the instant at which the first SN explodes. Any further star formation is neglected.

2.2 The two-phase medium within the cloud

The state of the ISM, the expansion of SNRs, and the mass and energy flows are modelled in a similar though simpler way as in Paper I. Let M_{dif} and M_{col} be the mass in the diffuse and collapsed phases [with $M_{\text{dif}} + M_{\text{col}} = (1 - f_*)M_{\text{cloud}}$], $\bar{\rho}_{\text{dif}}$ and $\bar{\rho}_{\text{col}}$ their average densities [$\bar{\rho} = 3M/(4\pi R_{\text{cloud}}^3)$], T_{dif} and $T_{\text{col}} (= 100 \text{ K})$ their temperatures, μ_{dif} and μ_{col} their mean molecular weights, and f_{dif} and f_{col} their filling factors (with $f_{\text{dif}} + f_{\text{col}} = 1$). Moreover, let $F_{\text{dif}} = M_{\text{dif}}/(M_{\text{col}} + M_{\text{dif}})$ be the fraction of gas in the diffuse phase. The assumption of pressure equilibrium implies $P_{\text{th}}/k = n_{\text{dif}}T_{\text{dif}} = n_{\text{col}}T_{\text{col}}$, from which it is easy to obtain

$$f_{\text{col}} = \left(1 + \frac{F_{\text{dif}}}{1 - F_{\text{dif}}} \frac{\mu_{\text{col}}}{\mu_{\text{dif}}} \frac{T_{\text{dif}}}{T_{\text{col}}} \right)^{-1} \quad (1)$$

(see equation 2 of Paper I).

The collapsed phase is assumed to be fragmented into cloudlets, whose mass spectrum N_{frag} is

$$N_{\text{frag}}(m_{\text{frag}}) dm_{\text{frag}} = N_0 (m_{\text{frag}}/1 M_{\odot})^{-2} dm_{\text{frag}}. \quad (2)$$

Here m_{frag} is the fragment mass in M_{\odot} and N_0 is a normalization constant such that $\bar{\rho}_{\text{col}} = \int N_{\text{frag}} m_{\text{frag}} dm_{\text{frag}}$. At variance with Paper I, we fix the exponent of the mass function to -2 , which is a natural value in the presence of turbulence (see e.g. Elmegreen 2002). The mass function is truncated below to a value m_1 set to $0.1 M_{\odot}$ (see Paper I and the discussions below) and above by requiring unit probability for the existence of at least one fragment [roughly $m_u = M_{\text{cloud}}/\ln(M_{\text{cloud}}/m_1)$]. A typical radius a_{frag} in parsecs is assigned to each cloud through the relation

$$m_{\text{frag}} = 0.104 \mu_{\text{col}} n_{\text{col}} a_{\text{frag}}^3 M_{\odot}. \quad (3)$$

In the following we will assume that the fragments are spherical.

Finally, we call v_{turb} the rms kinetic velocity of the ISM, $e_{\text{turb}} = 2v_{\text{turb}}^2$ the kinetic energy per unit mass, and P_{kin} the resulting kinetic pressure.

2.3 The fate of SNRs

One star with mass $> 8 M_{\odot}$ is formed for each $M_{*,\text{sn}} M_{\odot}$ of stars (taken to be $120 M_{\odot}$), so the total number of SNe is $N_{\text{sn}} = f_* M_{\text{cloud}}/M_{*,\text{sn}}$. The rate of SN explosions, R_{sn} , is then computed as

$$R_{\text{sn}} = \frac{f_* M_{\text{cloud}}}{M_{*,\text{sn}} t_{\text{life}}}, \quad (4)$$

where t_{life} is the difference between the lifetimes of an $8 M_{\odot}$ star and the most massive star, assumed to be $t_{\text{life}} = 27 \text{ Myr}$. Any time dependence of R_{sn} is neglected. Each SNR injects $E_{51} \times 10^{51} \text{ erg}$ of energy into the ISM. In the following, E_{51} is conservatively taken to be unity; however, its value is very uncertain and could be significantly higher. We call $E_{\text{sn}}(t)$ the total energy injected by SNe at time t . We assume that SNe are homogeneously distributed within the cloud; this influences the estimate of the porosity of SNRs. The effect of the spatial clustering of OB stars will be commented upon later.

Following McKee & Ostriker (1977) and Paper I, the blasts are assumed to expand into the more pervasive diffuse phase; the cold

dense fragments pierce the blast, which re-forms soon after the passage. We will ignore the effect of the collapsed phase on the blast. At variance with Paper I, we take into account the thermo-evaporation of cold clouds inside the expanding blasts, following the approach of McKee & Ostriker (1977) and Ostriker & McKee (1988); the saturation of thermo-evaporation is not taken into account. Assuming that the SNRs are not heavily mass loaded and do not lose thermal energy in the early free expansion stage, the expansion of the SNRs is divided into three stages. For sake of clarity, we report the main properties of the evolution of the SNRs in Table 1. At the beginning thermo-evaporation, which depends on the $5/2$ power of the average internal temperature, is very efficient, so that the interior hot gas

Table 1. Evolution of SNRs in the evaporative, adiabatic and PDS stages. R_s , v_s , \bar{T} , M_{sw} , M_{ev} , E_{th} and E_{kin} are respectively the radius, velocity, average temperature, swept mass, evaporated mass, and the thermal and kinetic energy of the SNR at a generic time t . The subscripts ev and pds refer respectively to the end of the evaporative stage and to the onset of the PDS stage. Here t_6 is time in units of 10^6 yr and T_6 is T_{dif} in units of 10^6 K . All these quantities are valid for solar metallicity and the simple cooling function of Cioffi et al. (1988) and Paper I.

Evaporative stage ($t < t_{\text{ev}}$ and $t < t_{\text{pds}}$)	
$R_s(t)$	$= 179 (E_{51} \Sigma)^{1/10} t_6^{3/5} \text{ pc}$
$v_s(t)$	$= 105 (E_{51} \Sigma)^{1/10} t_6^{-2/5} \text{ km s}^{-1}$
$\bar{T}(t)$	$= 1.66 \times 10^5 (E_{51} \Sigma)^{1/5} \mu_{\text{dif}} t_6^{-4/5} \text{ K}$
$M_{\text{sw}}(t)$	$= 5.91 \times 10^5 (E_{51} \Sigma)^{3/10} \mu_{\text{dif}} n_{\text{dif}} t_6^{9/5} M_{\odot}$
$M_{\text{ev}}(t)$	$= 1.34 \times 10^4 E_{51}^{4/5} \Sigma^{-1/5} t_6^{4/5} M_{\odot}$
t_{ev}	$= 2.28 \times 10^4 E_{51}^{1/2} \Sigma^{-1/2} (\mu_{\text{dif}} n_{\text{dif}})^{-1} \text{ yr}$
R_{ev}	$= 18.5 E_{51}^{2/5} \Sigma^{-1/5} (\mu_{\text{dif}} n_{\text{dif}})^{-3/5} \text{ pc}$
$M_{\text{ev}}(t_{\text{ev}})$	$= 651 E_{51}^{6/5} \Sigma^{-3/5} (\mu_{\text{dif}} n_{\text{dif}})^{-4/5} M_{\odot}$
t_{pds}	$= 4.86 \times 10^3 (E_{51} \Sigma)^{3/22} \mu_{\text{dif}}^{15/22} n_{\text{dif}}^{-5/11} \text{ yr}$
R_{pds}	$= 7.32 (E_{51} \Sigma)^{2/11} \mu_{\text{dif}}^{9/22} n_{\text{dif}}^{-3/11} \text{ pc}$
v_{pds}	$= 884 (E_{51} \Sigma)^{-1/22} \mu_{\text{dif}}^{-3/11} n_{\text{dif}}^{2/11} \text{ km s}^{-1}$
E_{th}	$= 0.55 E_{51} \times 10^{51} \text{ erg}$
E_{kin}	$= 0.45 E_{51} \times 10^{51} \text{ erg}$
Adiabatic stage ($t_{\text{ev}} < t < t_{\text{pds}}$)	
$R_s(t)$	$= 84.5 (E_{51}/\mu_{\text{dif}} n_{\text{dif}})^{1/5} t_6^{2/5} \text{ pc}$
$v_s(t)$	$= 33.1 (E_{51}/\mu_{\text{dif}} n_{\text{dif}})^{1/5} t_6^{-3/5} \text{ km s}^{-1}$
$\bar{T}(t)$	$= 4.65 \times 10^4 (E_{51}/n_{\text{dif}})^{2/5} \mu_{\text{dif}}^{3/5} t_6^{-6/5} \text{ K}$
$M_{\text{sw}}(t)$	$= 6.22 \times 10^4 E_{51}^{3/5} (\mu_{\text{dif}} n_{\text{dif}})^{2/5} t_6^{6/5} M_{\odot}$
t_{pds}	$= 1.27 \times 10^4 E_{51}^{3/14} n_{\text{dif}}^{-4/7} \mu_{\text{dif}}^{9/28} \text{ yr}$
R_{pds}	$= 14.7 E_{51}^{2/7} n_{\text{dif}}^{-3/7} \mu_{\text{dif}}^{-1/14} \text{ pc}$
v_{pds}	$= 455 E_{51}^{1/14} n_{\text{dif}}^{1/7} \mu_{\text{dif}}^{-11/28} \text{ km s}^{-1}$
E_{th}	$= 0.72 E_{51} \times 10^{51} \text{ erg}$
E_{kin}	$= 0.28 E_{51} \times 10^{51} \text{ erg}$
PDS stage ($t > t_{\text{pds}}$)	
$R_s(t)$	$= R_{\text{pds}}(4t/3t_{\text{pds}} - 1/3)^{3/10}$
$v_s(t)$	$= v_{\text{pds}}(4t/3t_{\text{pds}} - 1/3)^{-7/10}$
$*E_{\text{th}}(t)$	$= E_{\text{th}}(t_{\text{pds}}) \{0.398[1 - (t/1.169t')^{14/5}] + 0.602[(R_s/R')^{10} + 1]^{-1/5}[(t/t')^4 + 1]^{-1/9}\}$
$E_{\text{kin}}(t)$	$= E_{\text{kin}}(t_{\text{pds}}) [(t - t_{\text{pds}})/t_{\text{pds}}]^{-1/2}$
$M_{\text{snpl}}(t)$	$= M_{\text{sw}}(t) [1 - E_{\text{th}}(t)/E_{\text{th}}(t_{\text{pds}})]$

* Here $t' = t_{\text{pds}} \exp(1)$, $R' = R_s(t')$ and the first term in curly brackets is present only for $t_{\text{pds}} < t < 3.16t_{\text{pds}}$ (see Cioffi et al. 1988).

is dominated by the evaporated mass. In this case the evolution of the remnant is given by the evaporative solution shown in Table 1, where

$$\Sigma^{-1} = \frac{3f_{\text{col}}\phi}{\alpha^2} \left\langle \frac{1}{a_{\text{frag}}^2} \right\rangle_m. \quad (5)$$

In this equation the parameter ϕ relates the actual thermal conduction to the Spitzer value (used to compute the rate of thermo-evaporation), and its value depends sensitively on how effectively the magnetic fields quench thermal conduction. Besides, at fixed mass and density, spherical fragments present the smallest contact surface between the two phases, so any non-sphericity of the cloud will increase the effect of thermo-evaporation; this can be mimicked by an increase of ϕ . Moreover, evaporation acts on the low-mass tail of the fragment mass function, and thus depends on the value of m_1 ; keeping m_1 fixed, the uncertainty can be absorbed into ϕ . As a result, this parameter is highly uncertain, and every value below or around unity is equally likely. The parameter α relates the blast speed to the average sound speed of the interior, and is in this case $\alpha^2 = 8$. Finally, the quantity $1/a_{\text{frag}}^2$ is averaged over the mass distribution of clouds (equation 2). It is worth noting that Σ has the dimension of a surface (pc^2), and that it diverges (Σ^{-1} vanishes) if thermal conduction is quenched.

At later times the evaporated mass M_{ev} becomes smaller than the swept mass M_{sw} . From this moment we use the standard adiabatic solution, given again in Table 1. Eventually, the interior gas cools and collapses into a thin cold shell that acts as a snowplough on the ISM. For the evolution in the pressure-driven snowplough (PDS) stage, we use the analytical model proposed by Cioffi, McKee & Bertschinger (1988), given again in Table 1, which fits reasonably well their detailed 1D hydrodynamical simulations (confirmed by Thornton et al. 1998).

The PDS stage can be reached when the blast is still in the evaporative regime. In this case we pass directly to the PDS solution of Cioffi et al. (1988), as the drop in the density of the internal hot gas is very likely to quench thermo-evaporation.

The thermal energy of the hot interior gas in the evaporative and adiabatic stages is respectively 55 and 72 per cent, the rest being kinetic. In the PDS stage the evolution of the thermal energy is given by equation (3.15) of Cioffi et al. (1988) (reported in Table 1), while the kinetic energy is assumed to decay as $[(t - t_{\text{pds}})/t_{\text{pds}}]^{-1/2}$; this follows from assuming that all the mass and kinetic energy is in the expanding shell, so that $E_{\text{kin}} = M_{\text{sw}}v_s^2/2$, with $M_{\text{sw}} \propto R_s^3$, $v_s \propto R_s/t$ and $R_s \propto t^{0.3}$; this is valid for $t \gg t_{\text{pds}}$. The interior mass is assumed to collapse into the snowplough at the same rate at which thermal energy is lost.

The SNRs stop expanding in the following cases: (i) Remnants stall by pressure confinement; this happens when the velocity of the blast equates to the larger of the kinetic and the thermal velocity of the ISM. (ii) The porosity of the blasts, defined as $Q = R_{\text{sn}} \int_0^t R_s^3(t) dt / R_{\text{cloud}}^3$ (and computed considering all the evolutionary stages of the SNRs), reaches unit values. The stopping time t_{stop} of the blast thus corresponds to the earlier of these events.

The porosity given above is valid for a homogeneous distribution of SNRs. The non-uniform spatial distribution of OB stars will influence the estimate of Q if the radius R_{stop} of the SNRs is small or comparable to the typical distance between associations. This is not the case; we have verified that in most cases the stopping radius R_{stop} of the SNR is similar to the initial size of the cloud. This confirms the validity of the uniform distribution of SNRs as a first approximation.

2.4 Mass and energy budget

The onset of a PDS is important not only for its effect on the evolution of the blast but also for its effect on the diffuse phase, which is shocked to high temperature in the evaporative or adiabatic stage but compressed and cooled in the PDS stage.

The rate at which the diffuse phase is swept by the ISM is $\dot{M}_{\text{sw}} = R_{\text{sn}}M_{\text{sw}}(t_{\text{stop}})$. Each SNR causes the following mass flows: (i) some collapsed mass M_{ev} is evaporated to the diffuse phase; and (ii) some diffuse mass M_{snpl} is collapsed if PDS is reached. Both quantities are given in Table 1 and are always computed at the time t_{stop} . In particular, the evaporated mass is given by the time-dependent term of Table 1 for $t_{\text{stop}} < t_{\text{ev}}$, while it remains constant after t_{ev} (or t_{pds} whenever it is smaller). The evaporation and PDS mass flows are then

$$\dot{M}_{\text{ev}} = R_{\text{sn}}M_{\text{ev}}(t_{\text{stop}}), \quad (6)$$

$$\dot{M}_{\text{snpl}} = R_{\text{sn}}M_{\text{snpl}}(t_{\text{stop}}). \quad (7)$$

Radiative cooling of the diffuse phase leads to a global decrease of thermal energy. In this process the density peaks cool dramatically and thus move to the collapsed phase, giving rise to a cooling mass flow

$$\dot{M}_{\text{cool}} = f_{\text{cool}} \frac{M_{\text{dif}}}{t_{\text{cool}}}. \quad (8)$$

As noted in Paper I, the fraction f_{cool} depends on the detailed density structure of the diffuse phase, which is very difficult to predict without full-blown MHD simulation; notably, thermal conduction also influences it. Thus f_{cool} is left as a free parameter. The cooling time is

$$t_{\text{cool}} = \frac{3kT_{\text{dif}}}{n_{\text{dif}}\Lambda(T_{\text{dif}})}, \quad (9)$$

and is computed using the cooling function $\Lambda(T)$ of Sutherland & Dopita (1993);¹ solar metallicity will be used throughout the paper. To avoid overcooling at the beginning of the integration, a heating source is assumed to be present, such as to balance cooling for the diffuse phase present at the initial time. This is justified by the presence of the same UV photons responsible for the destruction of the cloud, and has an effect only during the first stages of evolution.

The thermal energy of the diffuse phase E_{dif} is lost by radiation at a rate

$$\dot{E}_{\text{cool}} = \frac{E_{\text{dif}}}{t_{\text{cool}}}. \quad (10)$$

The diffuse phase gains energy by blasts at a rate

$$\dot{E}_{\text{fb}} = R_{\text{sn}}E_{\text{th}}(t_{\text{stop}}). \quad (11)$$

This includes energy in both the evaporated and heated gas. The rate of energy loss by snowploughs is

$$\dot{E}_{\text{snpl}} = \dot{M}_{\text{snpl}}T_{\text{dif}} \frac{3k}{2\mu_{\text{dif}}m_p}, \quad (12)$$

where k is the Boltzmann constant and m_p the proton mass.

The kinetic energy per unit mass e_{turb} , measured in $\text{km}^2 \text{s}^{-2}$, of the collapsed phase decays through turbulent cascade as suggested by Mac Low (2002, 2003):

$$\dot{e}_{\text{dis}} = 6 \times 10^{-7} v_{\text{turb}}^3 L_d^{-1} \text{km}^2 \text{s}^{-2} \text{yr}^{-1}. \quad (13)$$

¹ We warn the reader that the analytical quantities given in Table I are computed using the very simple cooling function suggested by Cioffi et al. (1988) and used in Paper I.

Here L_d is the driving scale of the turbulence (in parsecs), taken to be twice the final diameter of the SNR (Matzner 2002; Mac Low 2003), or $4R_{\text{stop}}$. The kinetic energy is continually replenished, provided that the coherent velocity field of the expanding SNRs is randomized by overlapping blasts. The fraction of kinetic energy that goes out of the cloud as a coherent velocity field is estimated as the ratio between the initial external area of the cloud (the one that contains all the stars) and the sum of all the areas of active blasts:

$$f_{\text{exit}} = \frac{1}{R_{\text{cloud},i}^2} \int_0^{t_{\text{stop}}} R_s^2(t) dt. \quad (14)$$

As for the porosity, the integral is computed taking into account the evolution of $R_s(t)$ in all the stages up to t_{stop} . Of course f_{exit} is not allowed to exceed unity. The kinetic energy used to drive turbulence is then

$$\dot{e}_{\text{fb}} = 5.03 \times 10^7 (1 - f_{\text{exit}}) \frac{R_{\text{sn}} E_{\text{kin}}}{M_{\text{dif}} + M_{\text{col}}} \text{ km}^2 \text{ s}^{-2} \text{ yr}^{-1}. \quad (15)$$

Here $5.03 \times 10^7 = 10^{51} \text{ erg} / (10^5 \text{ cm})^2 M_{\odot}$.

The thermal energy of the diffuse phase and the kinetic energy not used to drive turbulence are available for driving a superbubble (SB) into the external two-phase ISM with densities of ‘hot’ and ‘cold’ phases n_h and n_c (these phases have the same mean molecular weights as the diffuse and collapsed ones). The exact modelling of the SB is beyond the scope of this paper, but the radius R_{cloud} of the destroyed cloud will expand with the SB. To follow this expansion we use some results that are valid in the adiabatic SB solution (Weaver et al. 1977; Paper I). The velocity of the SB is assumed to be

$$v_{\text{sb}}(t) = 89.5 \left(\frac{L_{38}}{\mu_{\text{dif}} n_h} \right)^{1/3} R_{\text{sb}}^{-2/3} \text{ km s}^{-1}, \quad (16)$$

where R_{sb} is in parsecs and the mechanical luminosity L_{38} , in units of $10^{38} \text{ erg s}^{-1}$, is

$$L_{38} = 3.16 \times 10^5 (E_{\text{th}} + f_{\text{exit}} E_{\text{kin}}) R_{\text{sn}}. \quad (17)$$

The total energy used to drive the SB will be $E_{\text{sb}} = \int L_{38} dt$. Moreover, we identify the radius of the shocked wind as the time-dependent radius of the cloud, R_{cloud} , and set it to $0.86R_{\text{sb}}$. In this way R_{cloud} expands at a velocity

$$v_{\text{exp}}(t) = 0.86 v_{\text{sb}}(R_{\text{cloud}}/0.86). \quad (18)$$

The adiabatic expansion of the cloud leads to a further energy loss term for the diffuse phase. According to Weaver et al. (1977), a fraction 6/11 of the injected energy is given to the shocked external ISM. The energy lost by adiabatic expansion is then simply set as

$$\dot{E}_{\text{ad}} = \frac{6}{11} \dot{E}_{\text{fb}}. \quad (19)$$

We warn the reader that the predicted T_{dif} depends sensitively on how the \dot{E}_{ad} term is modelled.

From all the mass and energy flows listed above, the following system of equations can be written:

$$\begin{aligned} \dot{M}_{\text{dif}} &= -\dot{M}_{\text{cool}} - \dot{M}_{\text{snpl}} + \dot{M}_{\text{ev}}, \\ \dot{M}_{\text{col}} &= \dot{M}_{\text{cool}} + \dot{M}_{\text{snpl}} - \dot{M}_{\text{ev}}, \\ \dot{E}_{\text{dif}} &= -\dot{E}_{\text{cool}} - \dot{E}_{\text{snpl}} + \dot{E}_{\text{fb}} - \dot{E}_{\text{ad}}, \\ \dot{e}_{\text{turb}} &= -\dot{e}_{\text{dis}} + \dot{e}_{\text{fb}}. \end{aligned} \quad (20)$$

This set of equations, together with equation (18) for R_{cloud} , is integrated with a standard Runge–Kutta code (Press et al. 1992).

3 RESULTS

The dynamical evolution of the system shows qualitative trends that are present for a very wide range of initial conditions and parameters. These trends are well illustrated by the example shown in Fig. 2, relative to a cloud with $M_{\text{cloud}} = 10^6 M_{\odot}$, with initial conditions $M_{\text{dif}} = M_{\text{col}} = (1 - f_{\star}) M_{\text{cloud}}/2$, $T_{\text{dif}} = 10^4 \text{ K}$ and $v_{\text{turb}} = 10 \text{ km s}^{-1}$. Parameter values are set to $E_{51} = 1$, $\phi = 0$ and $f_{\text{cool}} = 0.1$. The initial radius of the cloud is set using the same equation (3) with the external ‘cold’ phase density n_c in place of n_{col} ; for the external ISM, as in Paper I we use $n_c = 10$ and $n_h = 10^{-3} \text{ cm}^{-3}$, values typical for a galaxy disc. The figure shows the evolution of the masses of the two phases (M_{dif} and M_{col}), the energy released by SNe (E_{sn}) versus the energy used to drive the SB (E_{sb}), the mass flows (\dot{M}_{sw} , \dot{M}_{cool} , \dot{M}_{snpl} and \dot{M}_{ev}), the thermal energy flows (\dot{E}_{cool} , \dot{E}_{snpl} , \dot{E}_{fb} and \dot{E}_{ad}), the state of the ISM (T_{dif} , n_{dif} , n_{col} , P_{th} , P_{kin} and v_{turb}), and the quantities characterizing the expansion of the cloud within the SB (R_{cloud} , L_{38} , v_{exp} and f_{exit}).

At the starting time the cloud is dense enough to allow SNRs to go into the PDS stage before being stopped. This creates a strong mass flow from the diffuse to the collapsed phase, with a dramatic drop of thermal pressure and densities of both phases. This increase of the mass of the collapsed phase does not imply a re-formation of the molecular cloud, as the fragments will be spread out within the volume of the expanding SB; they will later mix with the external cold phase. In this early stage, pressure is dominated by the kinetic contribution due to the turbulent motion of the cold phase. The porosity of SNRs soon reaches unit values, which are maintained throughout the evolution. When the diffuse phase is significantly depleted, the SNRs merge before getting into the PDS stage; this happens in this example after 1.3 Myr. At this point energy is efficiently injected into the diffuse phase, whose temperature starts to increase. Once mechanical heating overtakes the effective heating term introduced in the equation, cooling becomes the dominant mass flow. This induces a further drop in the mass of the diffuse phase, which stabilizes after ~ 3 Myr to a constant value. From that moment the fraction of diffuse to collapsed mass and the density of the collapsed phase remain constant, while the other quantities follow the expansion of the cloud. Notably, the temperature of the diffuse phase increases gradually as a result of the efficient energy pumping. The energy used to drive the SB is significant after 1 Myr; energy losses are restricted to the first 3 Myr of evolution. Finally, the turbulent velocity v_{turb} remains between 10 and 25 km s^{-1} for the whole evolution.

The introduction of thermal conduction changes the details of the evolution but not its main properties. Fig. 3 shows the case with $\phi = 0.3$; the results depend only weakly on the value of ϕ as long as it is comparable to unity. The snowplough and cooling mass flows are contrasted by evaporation, which however becomes dominant only after a few Myr. The process of collapse of the diffuse phase is completed in some 3.5 Myr, but after that time the fraction of diffuse mass increases steadily. Owing to the higher density of the hot phase, SNRs go to the PDS stage for the first 5.4 Myr, with a consequent increase of energy losses. The structure of the ISM is similar to before, but, because of its higher density, the diffuse phase is considerably colder and thermal pressure consequently lower. Owing to the higher n_{dif} , SNRs are confined at a smaller radius and f_{exit} never reaches unit values; this implies that some fraction of the kinetic energy is dissipated locally by turbulence. The evolution of the resulting SB is very similar, because of the weak dependence of its expansion velocity on mechanical luminosity (equation 16).

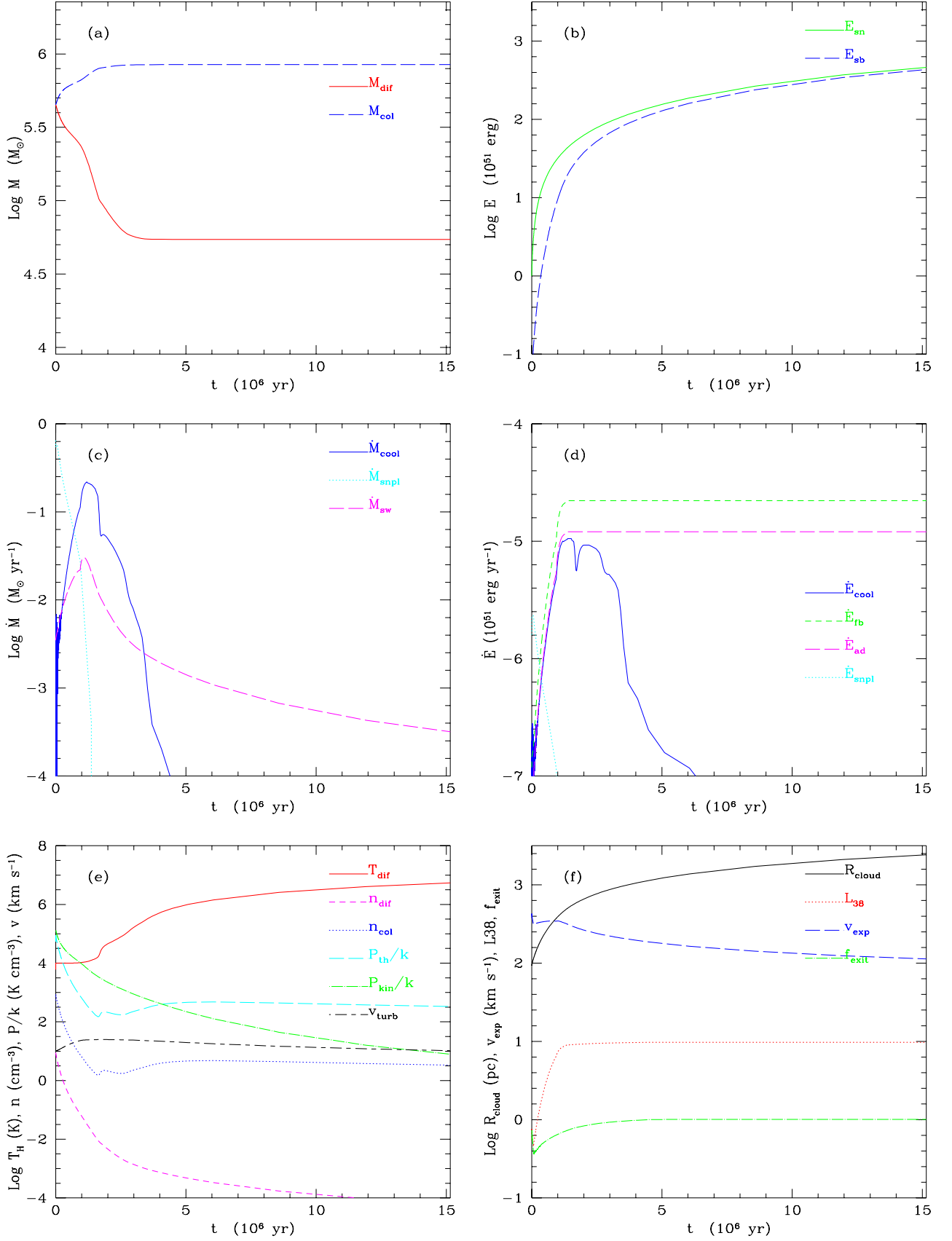


Figure 2. Evolution of a cloud with $M_{\text{cloud}} = 10^6 M_{\odot}$ for the reference choice of parameters given in the text. (a) Mass in the two phases. (b) Energy used to drive the SB compared to that injected by SNe. (c) Mass flows, including the rate at which mass is swept by SNRs. (d) Energy flows. (e) State of the ISM. (f) Mechanical luminosity and expansion of the SB.

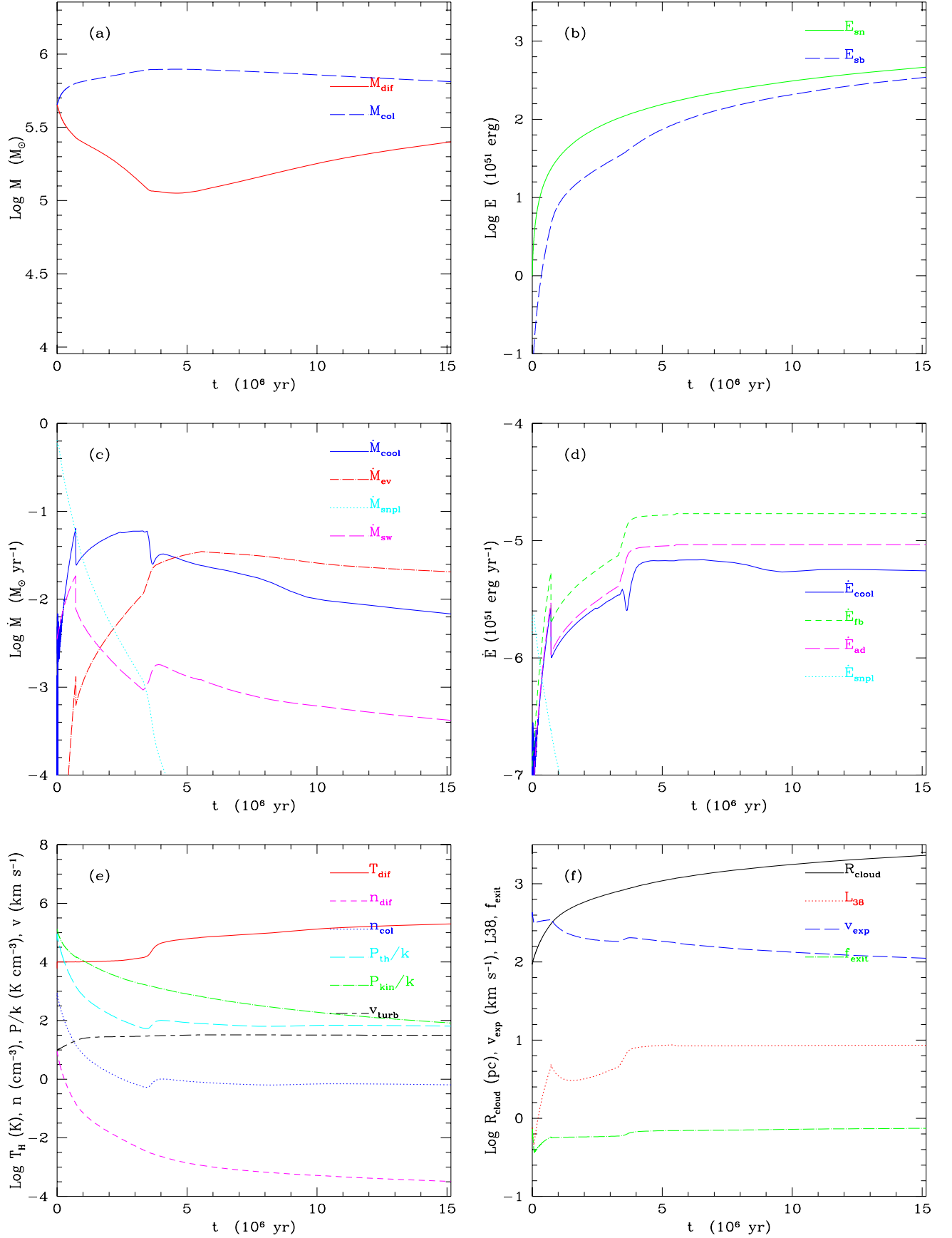


Figure 3. The same as Fig. 2, for the example with $\phi = 0.3$.

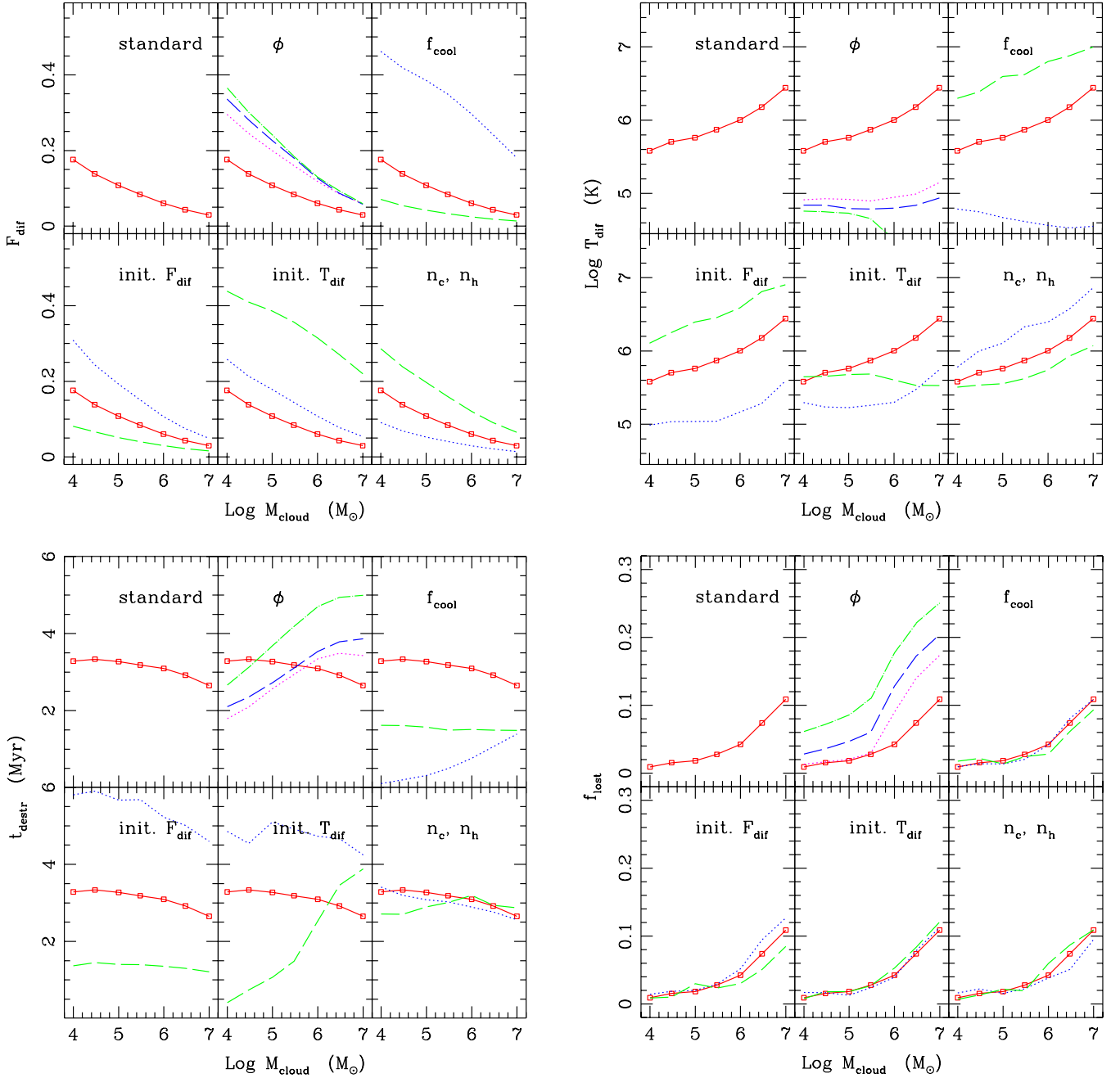


Figure 4. Plots of F_{dif} , T_{dif} (both at 5 Myr), t_{destr} and f_{lost} for many systems as a function of cloud mass M_{cloud} . Here ‘standard’ refers to the choice of parameters of Fig. 2, and is replicated in all panels. For ϕ , the dotted, dashed and dot-dashed lines refer to $\phi = 0.1, 0.3$ and 1 . For f_{cool} , the dotted and dashed lines refer to $f_{\text{cool}} = 0$ and 0.3 . For initial F_{dif} , the dotted and dashed lines refer to $F_{\text{dif}} = 0.9$ and 0.2 . For initial T_{dif} , the dotted and dashed lines refer to $T_{\text{dif}} = 3 \times 10^4$ and 10^5 K. For n_c, n_h , the dotted line refers to $n_c = 100, n_h = 10^{-2} \text{ cm}^{-3}$, and the dashed line refers to $n_c = 1, n_h = 10^{-4} \text{ cm}^{-3}$.

The system has been evolved with many combinations of initial conditions and parameter values. Fig. 4 presents, as a function of cloud mass, the fraction of diffuse ISM F_{dif} at 5 Myr, the temperature T_{dif} of the diffuse phase at the same time, the time t_{destr} required by the SNe to complete the destruction of the cloud (defined as the time at which the mass of the diffuse phase gets smaller than 5 per cent more than its minimum), and the fraction f_{lost} of the total energy budget of SNe lost at 5 Myr. The quantities F_{dif} , T_{dif} and f_{lost} are measured at 5 Myr, as at this time the destruction of the cloud is concluded in most cases; at later times F_{dif} and f_{lost} are constant

in the absence of photo-evaporation, but increase otherwise, while T_{dif} increases. However, it must be noted that the size of the cloud at this point is larger than the typical size of galaxy discs, so the applicability of this model at late times is doubtful.

For the standard choice of parameters and initial conditions (as that used in Fig. 2), from 3 to 18 per cent of the mass ends up in the diffuse phase, with T_{dif} ranging from 4×10^5 to 2.5×10^6 K; smaller clouds have lower R_{sn} values, so they maintain more diffuse matter to a lower final temperature. These two trends tend to compensate each other, so the thermal energy contained in the diffuse phase is

roughly proportional to the cloud mass. The time t_{destr} is ~ 3 Myr and depends only weakly on the cloud mass, while the fraction of energy lost by radiation is well below 10 per cent but for the most massive clouds.

When evaporation is switched on, the amount of diffuse matter increases significantly, especially for smaller clouds, while its temperature decreases to 10^5 K. This trend is stronger for larger ϕ values, although the dependence on the actual ϕ value is weak. As a result of the lower temperature, the thermal energy of the diffuse phase is lower than the no-evaporation case. Destruction times remain between 2 and 5 Myr, while radiation losses increase but remain generally lower than 20 per cent.

The other panels show what happens for the non-evaporative case when the parameter f_{cool} , the initial conditions (F_{dif} or T_{dif}) or the external densities are varied. In general, where more diffuse mass is obtained, its temperature is lower, so the thermal energy in the diffuse phase does not vary as strongly as F_{dif} or T_{dif} . The destruction time in most cases ranges from 1 to 5 Myr, while the fraction of energy lost is quite stable. At variance with what was found in Paper I, the results of the integration depend very sensitively on the uncertain parameter f_{cool} , and thus on the detailed density structure of the ISM. Moreover, they depend significantly on the state of the cloud when the SNe start to explode. Besides, the dependence on the external medium is not strong, though it is important to notice that with a denser external ISM F_{dif} tends to be lower and T_{dif} higher.

A detailed justification of all the trends visible in Fig. 4 would shed some light on the dynamics of the system, at the cost of a lengthy discussion. The most important information that this analysis yields is a direct impression on the robustness of the predictions.

4 CLOUD DESTRUCTION IN THE ADIABATIC CONFINEMENT REGIME

The system of equations (20) is valid as long as many SNe concur in determining the evolution of the system. More specifically, many SNe must explode in the first 3–5 Myr, which implies (for $t_{\text{life}} = 27$ Myr) a total number of SNe $\gg 10$ and then a cloud mass $M_{\text{cloud}} \gg 10^4 M_{\odot}$. For small clouds, the collapse of the diffuse phase and the onset of adiabatic confinement before PDS take place before the second SN manages to explode. In this case the present model simply does not apply.

As shown in Paper I, such small collapsing clouds are not found in spiral galaxies, where the Jeans mass (including non-sphericity and turbulent support) is rather high. This is a predicted result of the feedback regime in which SBs blow out of the disc, injecting their energy directly into the halo more than into the ISM. If the system is thicker or denser than a typical galaxy disc, SBs are kept pressure-confined by the hot phase, so they inject all of their energy into the ISM, which is then characterized by a much higher pressure and temperature of the hot phase. In this condition the Jeans mass is considerably lower, and collapsing clouds range from 2000 to 10 000 M_{\odot} . As a consequence, only a bunch of SNe explode in each of them (this is especially true if f_{\star} is set to a low value).

Let us consider the case of a $M_{\text{cloud}} = 2000 M_{\odot}$ uniform cloud with density n_c as large as 10^3 cm^{-3} , and let us call $M_{2000} = M_{\text{cloud}}/2000 M_{\odot}$ and $n_{1000} = n_c/1000 \text{ cm}^{-3}$. Then R_{cloud} , computed from equation (3), will be

$$R_{\text{cloud}} = 2.5 M_{2000}^{1/3} n_{1000}^{-1/3} \text{ pc.} \quad (21)$$

Neglecting for the moment photo-evaporation and any previous heating by UV photons, the SNR will go into the PDS stage well

before exiting the cloud, as

$$R_{\text{pds}} = 0.75 n_{1000}^{-3/7} \text{ pc.} \quad (22)$$

The blast will reach the outer boundary of the cloud after

$$t_{\text{out}} = 1.01 \times 10^4 M_{2000}^{1.11} n_{1000}^{-0.25} \text{ yr,} \quad (23)$$

with a final velocity of

$$v_s = 69 M_{2000}^{-0.77} n_{1000}^{-0.08} \text{ km s}^{-1}, \quad (24)$$

high enough not to be confined by the thermal or kinetic pressure of the cloud. At this point it will accelerate and fragment, spreading around the mass of the star-forming cloud. In this process it would lose nearly all of its energy. Any further SN would then explode in the rarefied bubble, easily reaching the outer boundaries of the cloud and merging with the external hot phase. The fate of secondary SNe is very difficult to predict, but a rule of thumb would suggest that, while the energy of the first SN is lost, a significant fraction of the others will be injected into the medium. In this case the fraction of reheated matter is likely to be rather low, in agreement with the extrapolation of the results of Fig. 4.

According to Matzner (2002), a single H II region can destroy a small molecular cloud. However, while UV photons can destroy all molecules and make the cloud unbound, thus lowering the average density of the cloud, it is likely that, for an external hot phase with $P/k \sim 10^5 \text{ K cm}^{-2}$ and $T_h \sim 10^7 \text{ K}$, the region in which the first SN explodes will be much denser than the external hot phase. The SN will thus lose all of its energy and create a hot rarefied bubble in place of an overdensity.² So, the tentative conclusions given above remain valid also in the case of preheated clouds.

5 DISCUSSION AND CONCLUSIONS

Type II SNe are probably the most important source of stellar feedback, but they explode in the densest regions of the ISM, the star-forming molecular clouds. The energetic input by expanding H II regions and stellar winds can self-limit star formation to a low efficiency and destroy the cloud in ~ 10 Myr. While the very first SNe will likely remain trapped within the H II regions, the bulk of them will explode when the cloud is already in the process of being destroyed.

Under the assumption of a two-phase medium in pressure equilibrium, the system evolves into a configuration where most mass is in a collapsed, low-filling-factor cold phase, while most volume is filled by a hot pervasive phase, able to confine the expanding SNRs while they are still in the adiabatic stage. In this way most energy is efficiently pumped into the diffuse phase and used to power an SB expanding in the external medium. This is a very important point: thanks to the multiphase nature of the ISM, only a few per cent of the energy injected by Type II SNe is lost to radiation.

The destruction of the cloud is completed by SNe in ~ 3 Myr, with a loss of energy of ~ 5 –10 per cent, to which one might add the energy of the very first SNe (roughly one per OB association) that are kept trapped within the H II regions. At the end of this process, a fraction of mass of the original cloud, ranging from 5 to 30 per cent, is heated to a temperature ranging from 10^5 to 10^7 K. This last quantity is especially uncertain; it depends sensitively on very uncertain parameters like ϕ and f_{cool} , on the specific initial conditions, and also on the way energy is given to the external ISM

² This can be checked by considering that $R_{\text{pds}}/R_{\text{cloud}} \propto n_{1000}^{-0.09}$ and $v_s \propto n_{1000}^{-0.08}$.

to drive the SB. On the other hand, the total thermal energy given to the final diffuse phase is more robust. Anyway, the choices used in Paper I of $F_{\text{dif}} = 0.1$, $T_{\text{dif}} = 10^6$ K and $f_{\text{lost}} \sim 0$ are justified by these results.

Excluding the very first explosions, SNe start to explode after a few Myr, and complete the destruction of the cloud in ~ 3 Myr. In this case, star formation cannot last more than several Myr. The destruction time inferred by Matzner (2002) of 10–30 Myr, based on the role of H II regions alone, can then be overestimated by a factor ~ 2 –3. This would also apply to its predicted efficiency of star formation of ~ 10 per cent. Low values of $f_{\star} \sim 5$ per cent and of the duration of star formation, $\lesssim 10$ Myr, are indeed in good agreement with observations (see e.g. Carpenter 2000; Elmegreen 2000).

These numbers refer to relatively large star-forming clouds, expected in galaxy discs where SBs are able to blow out in the vertical direction. In this case, only 5–10 per cent of the energy budget of SNe is injected into the ISM (Paper I), while a similar amount is lost in the destruction of the cloud. The rest of the budget, ~ 80 per cent, is injected into the halo, and is thus available to heat up the virialized halo gas, so as to prevent further cooling.

Smaller and denser clouds, predicted in Paper I to be associated to adiabatic confined SBs, are destroyed by one single SN. In this case the fraction of energy lost in the destruction is likely to be higher, while the fraction of reheated mass is likely to be lower.

Thermo-evaporation of cold clouds can play a significant role in this context. When ϕ is not negligible, the diffuse mass at the final time is more abundant and colder, and the energy loss is greater. However, thermo-evaporation does not change the qualitative behaviour of the system, and its contribution is still smaller than the uncertainties connected to the values of the other parameters. As a consequence, the main contribution to the reheating of the cold phase could be simply due to the residual effect of photo-evaporation by H II regions.

While it is clear that only high-resolution MHD simulations of the ISM, able to include all the relevant physical processes in play, will be able to provide in the future robust quantitative predictions for the destruction of a star-forming cloud, the calculations presented here show that, thanks to the multiphase nature of the ISM, a great part of the energy from SNe will be able to leave the star-forming regions, thus being available to regulate the formation of galaxies.

ACKNOWLEDGMENT

The author thanks Chris Matzner for discussions.

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