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Strada Costiera 11

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"MAGISTER PHILOSOPHIAE"

MULTICOMPONENT SELF-CONSISTENT MODELS OF STAR FORMATION AND INTERSTELLAR MEDIUM

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Supervisor: Prof. G. Barbaro

Candidate: Paola Mazzei

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I N D E X

I N T R O D U C T I O N

In the last two decades new obsevations have substantially improved our knowledge of the interstellar medium (ISM), invalidating the old picture (Field 1965) and leading to a new interpretation of its state and evolution and of the process of star formation.

The main points of this change are:

a) UV and X observations have revealed the existence of a hot component ($T \simeq 10^6$ K) capable of surviving for a long time, whose pressure is about ten times larger than that of the other components of the ISM. It is generally believed that the supernova explosions are most likely responsible for the creation of such hot gas.

From the analysis of the whole set of data concerning the ISM a picture emerges of a system with a violent dynamic behaviour, in which shocks are very common and interactions between the different components play a fundamental role in determining its state (McCray and Snow 1979).

A theoretical interpretation of the new observational panorama has been developed by McKee and Ostriker (1977), confined however to the equilibrium configurations; a further model has been proposed by Habe et al. (1981) in which the evolution of the ISM is followed, the energy input being supplied by supernovae and by a radiation field produced by stars and supernova remmants (SNR).

b) The matrix from which stars are generated, which was usually identified with the diffuse HI clouds, from the recent observational evidence has been now transferred to the clouds of molecular hydrogen (Turner 1984). Essentially unobserved until a few years ago, they contain a large fraction of the galactic gas; CO surveys have allowed the determination of the galactic H_2 distribution and the estimate of mass and dimensions of the clouds. More difficult is the study of their internal structure and dynamic behaviour: however it turns out that the clouds are characterized by clumps and entangled shapes; the nature of the internal velocity field is probably turbulent (Fleck 1983, Elmegreen, 1986).

c) Observations in the UV and IR regions of the spectrum have shown that the process of star formation, and particularly of massive stars, is often started by supersonic collisions. Collisions between clouds, of clouds with cold shells of HII regions and SNRs seem to provide the most likely triggering mechanisms (Woodward 1978 and references therein).

From all these considerations it follows that the process of star formation is thightly bound to the nature and evolution of the ISM and must be analyzed within a multicomponent model, in which interactions between the different components are accurately treated.

Models of this type have been computed by Shore (1981, 1983), Ferrini and Marchesoni (1984), Fujimoto and Ikeuchi (1984), Bodifée and de Loore (1985) in which the component interactions have been described in a simplified manner so as to allow the derivation of analytic solution or a discussion of the mathematical problem in terms of the general analysis of non-linear systems outlined by Poincaré. In these models the feedback mechanisms, which self-regulated the system evolution, are possible (also in the case of self-propagated star formation (Gerola and

Seiden, 1986)) but their physical basis is a mystery again, in particular is not clear if it is positive (i. e. the stars stimulate the formation of new stars) or negative (the OB stars inhibit the new star generations). A more careful description of the ISM has been adopted by Brand and Heathcote (1982) and Ikeuchi et al. (1984) but the assumptions about the star formation process are skipping or have gravitational nature, as Cowie (1980, 1981) proposed for the giant molecular clouds where the collapse would be induced by density waves.

I aim at analysing with careful detail, in the context of an evolutionary model of the ISM, some local processes of star formation arising from supersonic collisions and their dependence on the initial conditions of the medium. The purpose is to look into the reciprocal influence of the state of the ISM and the star formation and to define what different behaviour the last process can exhibit depending on the physical state of the medium. My analysis is confined, for now, to molecular clouds of intermediate-large masses ($M \leq 10^4$ Mo): more massive clouds confine in their interiors stars and HII regions for a large fraction of their lifetime thus making it more difficult to follow the evolution of the system. Probably this simplified approach could provide useful suggestions for the treatment of the general, more complicate problem.

In this work I present in the first section a brief description of the actually state of ISM and of its several components, in the second one I summarize the general properties and the location in our and in external galaxies of the molecular clouds emphasizing their observed internal turbulence: its presence may be determinant to stabilize the clouds and to affect the star formation efficiency. In the third one are described the principal features of star formation process in our and in external galaxies; it is derived that the star formation is propagating and the birth of massive stars is probably induced. Moreover I refer what it is now possible know about the star formation history. The fourth section contains the fundamental assumptions of my model which includes simple formulations of the induced star formation processes depending explicitly on the other model components. It is an one zone selfconsistent model which can permit to understand what and how many mechanisms can drive general results as those, for example, obtained by Gerola and Seiden's (1986 and references therein) models. In section five there are the first results and in the next one the conclusions.

S E C T I O N   1.

THE PICTURE OF THE INTERSTELLAR MEDIUM

Introduction

I summarize here a few observational evidences which have deranged the quasi-static picture for our galaxy (Field 1965).
The ISM seems now constitued by several types of gas, i.e. by gas in different physical conditions.
It is possible to present a description, althoug roughly, of its state considering what and how many components we can distinguish: their distributions, filling factors and physical features.

The coronal gas

It has been revealed in the ultraviolet spectra of OB stars by Rogerson et al. (1973), Jenkins and Meloy (1974), York (1974) from OVI doublet resonance line. The initial hypothesis that this absorption had a nonstellar origin was confirmed in later work by York (1977) and by Jenkins(1978a,b), primarily on the basis of noncorrelation between the OVI and stellar velocities. Distances up to 500 pc. have been well-sampled in the OVI survey, with some coverage of distances as great as 1-2 kpc. The principal features of the OVI absorption are that it is seen in most directions, its strength correlates only weakly with distance and the lines are relatively broad for interstellar absorption. Both the degree of ionization and the line width argue for gas temperature of 2.5-7×10^5 K (York 1977).
There remains some uncertainty concerning possible circumstellar origins in the material swept up by stellar winds (Castor, McCray and Weaver 1975, Weaver et al. 1977). The detailed statistical

study of Jenkins (1978b), along with the existence of OVI absorption in the spectra of stars with weak or nonexistent winds, appear to favor an interstellar origin, however. These features can be originated by thermal conduction in the outer zones of clouds embedded in the coronal gas, as suggested by McKee and Ostriker (1977) and by Cowie et al. (1977).

Evidences for coronal gas at even higher temperature is found in the diffuse soft X-ray background (Williamson et al. 1974). The thermal nature of this emission has been confirmed by Inoue et al. (1979). The X-ray background at 200 eV. comes from coronal gas within 100 pc. of the sun; the soft X-ray background is rather patchy as well. The distance probed varies with direction and can be less than 100 pc. in directions containing moderately dense clouds.

In general the characteristic range of temperature and density for this regime which comes out from UV data is (Jenkins 1978a,b):

$$5.3 \leqslant \log T(K) \leqslant 5.9 \qquad -2.3 \leqslant \log n(cm^{-3}) \leqslant -1.5$$

The X-data instead suggest temperature such that:

$$\log T > 6.3$$

We can obtain the galactic filling factor for this component by its pressure (Myers 1978):

$$p/k = C(\eta)/f$$

The value of f is affected by the indetermination relative to the choice of the η parameter which, in its turn, must arise from the best-fit of the T-n distribution. Jenkins(1978) and Myers (1978) have obtained $0.0 \leqslant \eta \leqslant 1.0$ such that $0.3 \leqslant f \leqslant 0.8$; if we put

$p/k=3.7x10^3$ cm $^{-3}$ (McKee and Ostriker 1977) then f=0.5.

The idea that coronal temperatures may exist in the ISM was firstly proposed by Spitzer's (1956) classic paper on the galactic corona. The essential point is that coronal gas radiates very inefficiently by bremsstrahlung; this represents a sharp contrast with cooler gas which contains many partially ionized atoms that can radiate efficiently following collisional excitation. As a result, coronal gas, once creates in ISM, may persist for millions of years, even without a heat source.

Cox and Smith (1974) pointed out that galactic supernovae may occur at a rate sufficiently high to produce an interconnecting 'tunnel' system of coronal gas so that the ISM has the morphology of swiss cheese. It was well-known that the interiors of SNR consisted of coronal gas and that such gas should persist; a simple counting argument then shows that the interiors are likely to overlap. McKee and Ostriker (1977) have further developed this idea suggesting that the volume fraction of the hot gas may be so great that the ISM consists of disconnected regions of HI and HII embedded in a substrate of low density coronal gas. The important qualitative property shared by the two models is that the coronal gas is connected, so that much of the energy of shock waves resulting from SN explosions remains in the interconnected coronal region, where it is not easily lost to radiation.

The thermal conduction plays the most important role in the thermodynamic of the hot ISM. Because of the strong temperature dependence of the conductivity ($T\propto^{5/2}$), thermal conduction at the interfaces with the cooler regions, unimportant in the cooler ISM ($T\leqslant10^4$ K), may be the dominat cooling mechanism of the hot component and may cause the 'evaporation' of the interstellar clouds or the condensation of the hot gas on the cloud boundary (Cowie and McKee 1977, McKee and Cowie 1977) . Some fraction of the observed absorption features (OVI) probably originates in these conductive interfaces caused by the action of the stellar wind of the background star on its stellar environment, which produces an 'interstellar bubble' (Castor et al. 1975) with a structure similar to a SNR. The rest comes from other conductive interfaces in the intervening ISM (SNR or shocks in general).

Since this hot component has a pressure 10 times higher as the other ISM components, the regions filled by this gas tend to a rapid expansion.

This 'violent interstellar medium' comprising high-velocity and high-temperature gas, has largest implications on galactic ecology since it influences the cycle of interstellar grains (Draine and Salpeter 1979), the propagation of cosmic rays and the flow of gas through the galactic spiral structure and between the galactic disk and corona.

Warm gas

Shull and York (1977) and Shull (1977a) found high-velocity SiIII absorption components in the lines of sight of several high galactic latitude objects; between the other authors, Cowie, Songaila and York (1979) have mapped a variety of high-velocity interstellar clouds which are seen most strongly in SiIII, CII, CIII, and NII absorptions. Perdominantly negative velocities as high as 120 km/s (LSR) have been found. Cowie, Laurent and Vidal-

Madjar (1979) have found that these clouds can be observed in HI absorption, via the Lyman lines of HI of higher excitation which are weak enough so that the lower-velocity (20-30 km/s) components do not obscure the high-velocity absorption.

Naturally the optical data usually indicate the presence of cool gas while the UV measurements of SiIII lines refer to warmer gas and then clouds seen in optical and ultraviolet generally have different characteristics. Some attempts have been made to identify specific velocity components in different regimes. For example Habing (1969) and Hobbs (1971) found a few velocity and spatial coincidences between HI clouds and known high-velocity CaII components. More recently Giovanelli et al. (1978) have carried out 21-cm observations in directions suggested from optical and UV data with the purpose of intercepting high-velocity clouds. They found a number of coincidences.

This moderate-to high velocity gas is distinct from the coronal gas. For this 20000-100000 K material the SiIII line at 1206 A is a particularly sensitive tracer because of its large oscillator strength and because it corresponds to the dominat ionization stage for the appropriate temperature range; the electron density inferred for this gas from population of fine-structure levels in CII is $n_e \leq 1\ cm^{-3}$ (McCray and Snow 1979).

Following Turner (1979) this gas, cooler and more dense that the former, has:

$$2.9 \leq \log T\ (K) \leq 4 \qquad -1.0 \leq \log n\ (cm^{-3}) \leq 0$$

Myers (1978) suggests average values:

$$\bar{T} = 4.5 \times 10^3\ K \qquad \bar{n} = .36\ cm^{-3}$$

and a filling factor ≈1 if $p/k=10^3$ cm^{-3} or f=0.3 if $p/k=3.7x10^3$ (McKee and Ostriker 1977).

This component probably is due to shocks which heat and push the ICM or the clouds. The HII regions, however, are by definition large blisters in expansion containing considerable amount of this warm gas produced by the ionizing field in the surrounding gas.

Cold gas

This component has typically $n(cm^{-3})>1$, $T(K)<200$ and corresponds to classical cold medium of quasi-static models (Field 1965); now the recognized existence of hot, coronal gas, implies a general nonequilibrium situation of the ISM.

Molecules have been observed in clouds since the late 1930s when interstellar absorption lines from CH, CH^+ and CN were discovered in the visible spectra of several stars (for example by Dunham and Adams 1937). Molecular hydrogen was detected much later, using ultraviolet spectrometers above the atmosphere (Carruthers 1970). In the 1970s the relative abundance and temperature of H_2 was determined for over 50 nearby clouds from absorption-line observations by Copernicus satellite (Spitzer et al. 1973,1974).

We can distinguish between two kinds of clouds: molecular and diffuse clouds.

Simplifying assumptions limiting the degree of confidence of the obtained results are usually necessary to deduce cloud's general characteristics. As an example it is often assumed that some quantities are constant, among them I can list the gas to dust ratio and the spin temperature.

Diffuse cloud

If these consist of pure HI and their dimensions are constant, Myers (1978) estimates their average values:

$$\bar{T}=1.3\times10^{2}\ K \qquad \bar{n}=37\ cm^{-3} \qquad \bar{p}/k=3.1\times10^{3}\ cm^{-3}$$

It is obvious that this definition is affected by their assumed constant dimensions.

Turner (1979) defines them as characterized by a column density, $N(cm^{-2})$ between 2×10^{19} and 2×10^{21} assuming the total column density $N=N_H+2N_{H_2}$ inversly correlated with temperature as follows by the thermal equilibrium for this component: $\log N=a-b\log T$.

The lower limit for N is then the currently lowest detectable value (by 21-cm absorption techniques) while the upper limit represents the value above which the temperature becomes roughly indipendent of density; in fact when $A_V>1^m$ the UV radiation is completly absorbed by the outer layers of cloud, then the cooling rate depends only on the density and the b coefficient would be zero. At the low-N range, these clouds have no molecular content, while the higher-N clouds have appreciable amounts of H_2 observed optically (Savage et al. 1977), and CO, observed at $\lambda=2.6$ mm (Knapp and Jura 1976).

The distribution in sizes, based on statistical analyses of selective extinction, indicates two groups of clouds: the large ones with radii ≈35 pc, and the "standard" ones with radii of ≈5 pc (Spitzer 1978), ≈8 times more numerous. These two kinds are characterized by:

$$40\leqslant T(K)\leqslant150 \quad \text{and} \quad \bar{T}=80\ K$$

$$2 \leqslant n(cm^{-3}) \leqslant 10 \quad \text{and} \quad \bar{n}=3\ cm^{-3}$$

A rappresentative pressure for these clouds is $p/k=3700\ cm^{-3}$, although some are much lower.

Molecular cloud

Dense molecular clouds have been classified according to two schemes, both involving nothing more than a simple dichotomy of characteristics. In the Turner's scheme (from Turner 1979, Table 1.1) clouds were designated either "Giant Molecular Clouds" (GMC) or "Small Molecular Clouds" (SMC), and the line of demarcation was rather arbitrary, ≈1000 Mo (Turner 1984). This mass does seem to delimit regions of massive star formation which occur only in clouds exceeding this mass. In the other classification scheme (Evans 1978), clouds are described as Group A if the temperatures within them nowhere exceed 20 K, and Group B if they contain warm or hot cores exceeding 20 K. These latter cores are readly identified as star-forming regions. It happens that the Group A clouds bear an almost exact 1:1 correspondence with SMCs, and Group B clouds a similar (but slightly lower correspondence) with GMCs. Table 1.2 (from Turner 1984)) summarizes the physical characteristics in terms of the Group A and B categorization, but the correspondences with the SMCs and GMCs should be borne in mind.

The most important items in Table 1.2 are as follows:

(1) The demarcation temperature of 20 K is physically meaningful. Molecular gas with no internal heating sources, with densities $n>10^2\ cm^{-3}$ and optically opaque to UV will attain an equilibrium between heating of cosmic rays and cooling via CO rotational

TABLE 1.1.

-PHYSICAL CLOUD PROPERTIES-

TYPE	Mass (Mo)		Size (pc)	
	typical	range	mean	range
diffuse clouds	4(2)	?	5	≤1-?
isolated clouds	2.6(2)	5-1.3(3)	0.9	0.2-2.3
large globules	20	0.3-70	0.3	0.1-1.1
dark clouds + AB stars	1(4)	2.5(2)-7.6(5)	8	1-60
mol. clouds + OB stars	2(4)	1.5(3)-2.5(6)	30	3-170
molecular cores	1(3)	1(2)-5(4)	1	0.2-5.4
giant molecular clouds	>1(5)	7(4)-2.5(6)	60	30-170

From Turner (1979).

TABLE 1.2.

-PROPERTIES OF MOLECULAR CLOUDS-

	Group A (cold)		Group B (warm)	
	Envelope	Core(s)	Envelope	Core(s)
T_k(K)	10	10	10-20	20-100
n (cm^{-3})	1(2)-1(3)	1(4)-1(5)	1(2)-1(3)	3(4)-1(6)
diameter (pc)	1-10	0.1-1	10-200	1-3
M (Mo)	10-1000	1-100	1(3)-1(5)	1(2)-5(3)
M_j (Mo)	8-24	≈2	?	2-4
Strong IR?	No	No	No	Yes
Morphological types	globules cold dark clouds (SMC)		"giant molecular clouds" (GMC)	
Star formation?	possibly none ≈none earlier than A0		copious low mass stars often OB clusters	
No. in galaxy	globules: ≈25000 dark clouds ?		4000	
total mass	?		4(9) Mo	
motions (Δv)	0.2-3 km/s (supersonic)		3-15 km/s (supersonic)	

From Turner (1984)

transitions, the equilibrium temperature being of T_k=10 K . Typical protostellar heating sources representing OB stars will elevate the surrounding gas to T_k>20 K. Outside of the warm cores in GMCs, the gas has properties similar to those of SMCs.

(2) SMCs appear never to have associated stars of spectral type earlier than ≈A0 or perhaps late B, and may have no associated star formation at all. About half of all SMCs do have associated low-mass stars, usually of T-Tauri type. GMCs always have associated low-mass star formation, and usually have OB star formation as well. Points (1) and (2) explain why SMCs were known as "cold dark clouds" in earlier times.

(3) The Jeans mass is always exceeded for both groups. Thus they are gravitationally unstable, and should either be collapsing at roughly free-fall rate, or are supported by some internal agent.

(4) Internal motions are always supersonic in GMCs, and nearly always in SMCs. In the latter, subsonic motions are restricted to very small, localized clumps or cores.

(5) Although not indicated in Table 1.2, the galactic distribution of two groups of clouds is important to outline the picture of star formation. In particular, a growing body of observational evidence suggests that GMCs are created in, and largely restricted to spiral arms, while SMCs have a more uniform distribution within and between spiral arms.

It is once evident that the evolution of the ISM in the galaxies, and of the galaxies as a whole, are strongly dependent on the H_2 location. This is especially true in view of the apparent close association in our Galaxy between molecular clouds and star formation as it will clarified in the next section.

S E C T I O N   2.

MOLECULAR CLOUDS AND STAR FORMATION

Introduction

Molecular hydrogen is not easily observed in dense star-forming clouds. The clouds are usually too opaque for UV absorption line analysis, and H_2 has been recognized only by its collisional excitation of other molecules, and by the relative decrease in 21-cm emission or absorption line strength from the depletion of atomic hydrogen. Thirty years ago, Bok (1955) noted that the ratio of the HI column density to the dust extinction is much lower in local dark clouds than it is in diffuse clouds, and he conjectured that the missing hydrogen is in the form of undetected molecules.Similar studies by Mezaros (1968), Knapp (1972) and others also found a depletion of HI in dust clouds. Direct observations of trace molecules in star-forming regions began with the detection of OH and H_2CO in dust clouds at centimeter wavelengths, and of CO near HII regions at millimeter wavelengths (Elmegreen, 1986). H_2 was immediately identified as the dominant component of these clouds, even though it was not detected directly, because a total gas density of 10^3 cm^{-3} or more is required for collisional excitation of CO; only H_2 could be so dense and escape detection at 21 cm. Therefore 21-cm and extinction observations of star-forming regions often understimated the cloud masses and gas densities. This lead to erroneous conclusions about star formation. In many cases,in fact, even the most qualitative ideas about the star formation have been critically dependent on the quantitative properties of molecular clouds. These properties are derived from molecular-line observations and are clearly essential for determining the mechanisms of star formation. Observations in external galaxies have also revealed large amount of this component. In this section, after a brief description of molecular gas distribution in external galaxies and in our own galaxy, I summarize the most fundamental properties of molecular clouds to discuss how these properties have influenced the concept of star formation.

Molecular gas distribution

<u>In the external galaxies</u>.

An examination of the spiral galaxies known to contain CO reveals no correlation between CO abundance and any classical criterion such as morphological type or luminosity class (Morris and Rickard, 1982). Barred spirals show no substantive difference from normal spirals in CO content. At least for the spirals, it is still true that the distinctive features of galaxies with detected CO (dustiness, nuclear activity, etc.) also characterize some galaxies that currently show no CO emission.

The Magellanic-type irregulars are CO deficient compared to our Galaxy. Elmegreen et al. (1980) offer two reasons for this: (a) a lower CO abundance in the Irr than in the late-type spirals or (b) a mean CO excitation temperature that is a factor two or three lower than in our Galaxy, possibly reflecting a lower cosmic-ray heating rate. In galaxies of low metallicity (as at least some of Magellanic irregular are), a lower CO abundance could be accounted for by the increased CO formation time and by the increase of the photodissociation rate due to relatively smaller amounts of obscuring dust (as we will see below).

Some elliptical galaxies have also been searched, on the grounds that mass loss from their red giants could produce detectable amounts of CO (Zuckerman 1980). To date, the only reported detection is a tentative one in NGC 185 (Johnson and Gottesman 1981). The associated H_2 mass is about 10^4 Mo which is ≈10% of the mass seen in HI.

Finally, it must be noted the report of identifications of UV transitions of H_2 and CO in the absorption spectra of high-redshift quasars (Varshalovich, 1981), which indicate the presence of H_2 clouds in the disks of distant galaxies.

The data discussed by Morris and Rickard (1982) suggest a categorization of galaxies according to the degree of predominance of the central and disk sources. They define:

class 1 galaxies as having both strong central sources and well-defined molecular disks, with a monotonic decrease in the integrated intensity, P(CO), from center to edge;

class 2 galaxies have similarly strong central sources, but with surrounding molecular annuli, rather than complete underlying disks, and a significant and detectable minimum between the two component;

class 3 galaxies have well-defined annuli and absent or very weakly central sources [$P(CO)_{center}<0.2P(CO)_{disk}$];

class 4 galaxies show emission only from isolated HII regions or dust clouds in their disks;

class 5 galaxies have no detected CO emission at all.

Improved sensivity of observations will obviously shift the galaxies around in this scheme, moving them from class 4 to class 3, or from class 5 to any of others. In addition, improved angular

TABLE 2.1

-CLASSIFICATION OF GALAXIES BY CO EMISSION-

Class	Characteristic	Example
1	Central source plus disk	M51,NGC6946,IC342
2	Central source plus annulus	Milky Way
3	Annulus without central source	M31, M81
4	Emission from isolated regions	M33, LMC
5	No detectable emission	NGC6822, SMC

From Morris and Rickard (1982).

resolution may shift galaxies from class 1 to class 2. Still class 1, 3, and 5 seem to represent distinct types with different H_2 characteristics. Some rappresentative examples of each type are listed in Table 2.1 .

<u>In our own Galaxy</u>.

The original CO surveys (Scoville and Solomon, 1975; Gordon and Burton, 1976) have found a huge amount of H_2 in the Galaxy, $M_{H_2} \approx 5 \times 10^9$ Mo, Sanders et al. (1984) claim that the H_2 mass is less than 3.6×10^9 Mo in spite of the fact that, from cosmic gamma ray and other arguments, Lebrun et al. (1983) and Bhat et al. (1984) could hardly allow for $M_{H_2} > 10^9$ Mo. The 21-cm surveys have already suggested that the Galaxy contains about 10^9 Mo of neutral hydrogen within the solar circle; then the molecular content of our Galaxy is at least equal to the amount of HI gas.

It was formerly argued than atomic clouds were the seats of SF. A correlation between the amount of H_2 and the SFR was indeed shown by Talbot (1980) and he further showed that no correlation existed for atomic gas or total gas. Recently Rana and Wilkinson (1986a) have confirmed this conclusion for the SFR dependence on the molecular gas. In Fig. 2.1 (from Rana and Wilkinson 1986b) the ordinate readings on left margin correspond to $\log(\Sigma_{H_2}/\Sigma_{H_2 o})$ whereas those on the right to $\log(\psi_s/\psi_{so})$ assuming the conversion factor k=1.12 :$\psi_s \propto \Sigma_{H_2}^{k}$; Σ_{H_2} represents the H_2 surface density, ψ_s is the SFR and the index "$_o$" refers to the solar neighbourhood values. Superimposed to this plot are the curves representing the different estimates of <u>the distribution of the Σ_{H_2}</u> derived from the CO emissivity measurements in the Galaxy. Each distribution has been normalized to its quoted value in the solar neighbourhood. This naturally eliminates the existing differences in the absolute values of Σ_{H_2} in the solar neighbourhood, arising partly from the disagreeing absolute values of Σ_{H_2} of the CO emissivity and partly from the differences in the adopted values of the CO→H_2 conversion ratio (Sanders et al., 1984). The four continuous curves labelled B,C,S and R refer to H_2 distributions in the inner Galaxy averaged on either sides of the centre of the Galaxy, respectively given by Bhat et al. (1984,1985), Cohen et al. (1984), Sanders et al. (1984,1985) and Robinson et al. (1984). The measurements for the outer Galaxy (that is, for R_G>10 kpc) are fewer and are shown by dotted lines where the sampling is incomplete. Only Sanders et al. give an observational distribution of Σ_{H_2} for the outer Galaxy up to as far as 14.5 kpc but for the nothern declination only. Using a metallicity gradient of about -0.07 dex.kpc^{-1} for R_G>6 kpc and assuming that α (CO→H_2 conversion factor) varies inversely with metallicity, Bhat et al. suggest values that are represented by the dotted curve.

The data available on <u>the radial distribution of the present SFR</u> are normalized to their respective values in the solar neighbourhood (taken to be at R_G=10 kpc); the open circles and the open boxes represent the value of ψ_s derived by Smith et al. (1978) and Myers (1978) respectively, from studies of Lyman continuum emission from HII regions in the Galaxy; HII regions are visible from large distances, the galactic surveys seem to be quite extensive. The filled circles represent the SFR derived from the pulsar distribution (Lyne et al, 1985) and the crosses from SNR (Guibert et al., 1978). These surveys are obviously limited mainly

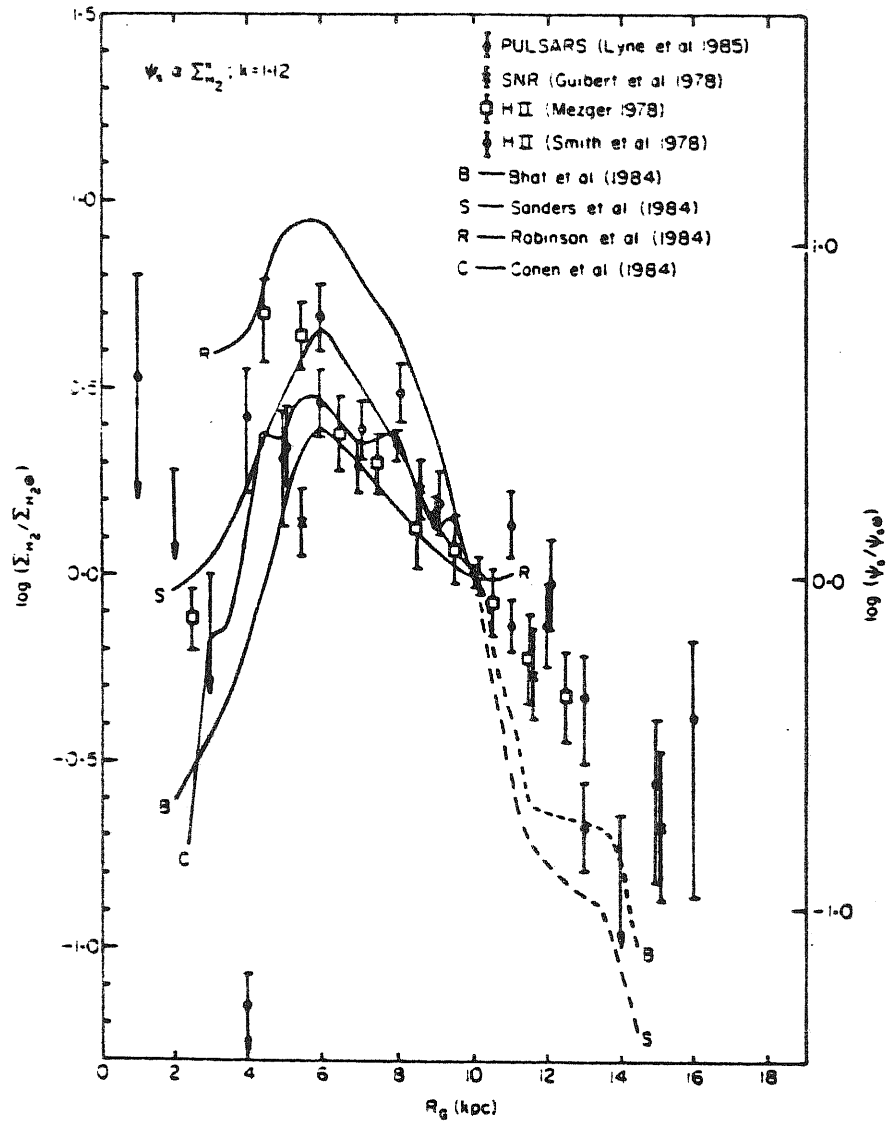


Figure 2. Present radial variation of star formation rate ψ, normalized to its value in the solar neighbourhood $\psi_{s\odot}$. The sources of data are noted in the figure. The same plot can be used to represent the present radial variation of the surface density of molecular hydrogen Σ_{H_2} in the Galaxy, just by rescaling the ordinate by a factor k, which has been taken to be 1.12. The radial variation of Σ_{H_2} derived from various CO surveys after normalizing at $R_G = 10$ kpc, including their references are shown by a family of curves marked with B, C, R, and S.

Figure 2.1 from Rana and Wilkinson (1986b).

to the solar side of the Galaxy but reasonable models for pulsar and SNR distributions over the whole Galaxy have been used to infer the SFR averaged over Galactocentric rings of different radii. However since the mass ranges of the progenitor stars that lead to the formation of pulsar and SNR are poorly known, the absolute values of the SFR can not be ascertained, and therefore, one should rather express the radial distributions relative to the value in the solar neighbourhood, as suggested by Lacey and Fall (1985).

From the figure it is clearly that the relation $\psi_s \propto \Sigma_{H_2}{}^k$ with k=1.12 holds within the solar circle; outside the solar circle, the correlation between the SFR data and those from CO surveys is rather poor but Rana and Wilkinson (1986b) interpret it as due to incompleteness of the CO survey data.

The general characteristic of star forming clouds

The observetional evidence indicates that <u>the stars form only in molecular clouds</u>. Why? An explanation has been proposed by Elmegreen (1986). It is clear that the star formation occur when part of an interstellar cloud collapses under the force of its own gravity, in other words the binding force from gravity in the cloud core exceeds the binding force from pressure in the remote external medium. The collapse can be spontaneous or stimulated (Elmegreen, 1978) but it is unavoilable to form stars. The existence of a gravitational threshold corresponds to a minimum value of the average cloud mass column density μ that is proportional to the square root of the external pressure p:

$$\mu>1.6(p/G)^{1/2}$$

where G is the gravitational constant. With the local value of the gas-to-dust ratio in the interstellar space makes μ is equal to 0.005 g cm^{-2} times the visual extinction A_V in magnitudes (Jenkins and Savage,1974). Thus the condition for strong internal gravity is approximately:

$$A_V>0.8(p/(3000k))^{1/2}$$

for a cloud in a typical environment with a pressure of ≈3000k. Molecules form where the opacity from dust is large enough to absorb most of the background stellar ultraviolet radiation, H_2 and CO, for example, have been found to occur in clouds when $A_V>0.5^m$ (Bally and Langer,1982). Coincidently this self-shielding threshold is the same as the mass column density threshold that makes a cloud strongly self-gravitating in the local environment. Thus, the local star-forming clouds are also molecular.

Not all of a star-forming cloud will be cold and molecular. The above discussion applies only to the strongly self-gravitating part of a cloud: the cloud core. Indeed molecular clouds should not be viewed as isolated clouds, but only as the opaque regions of more extended cloud complexes, which contain a large fraction of HI gas (Casoli et al. 1984) ; star-forming clouds should have warm envelopes, where the ultraviolet radiation from external starlight photodissociates molecules and heats the gas. Then the whole morphology of the SF regions is very diversified, in particular the molecular portion of the cloud can be the result of supersonic external or internal collisions (Hollenback and McKee 1979, McKee and Hollenbach,1980).

The molecular fraction of a star forming cloud depends on at least three properties of the overall environment (Elmegreen 1986):

(1) the heavy element abundance, because of (a) the role of dust opacity in shielding the molecules from the ultraviolet radiation; (b) the dependence of the molecule formation rates on the relative densities of the constituents (e. g. for CO) or on the total surface area of dust grains (for H_2); (c) the dependence of molecule formation rates on the thermal temperature which is determined by the heavy element cooling rate; and (d) the dependence of the external radiation field, and therefore of the dissociation rate, on the heavy element abundance. The external radiation field is related to the composition owing to the likely connection of metal abundance with the inital mass function and to the dependence of the ultraviolet flux from stars on their atmospheric opacities.

(2) The molecular fraction depends on the local star density, which estabilishes the flux of the ultraviolet radiation incident on the cloud. (3) It also depends on the cosmic ray flux, both because cosmic rays produce ionization in a cloud conditioning the formation rate of molecules by ion-molecule reactions, and because cosmic rays are an important heat source in cloud.

McKee and Hollenbach (1980) refer that for shocks incident upon relatively dense gas ($n_0 \lesssim 10^{2-3}$ cm^{-3}), H_2, CO, OH or H_2O molecules may dominate the post-shock cooling and a shock velocity of about 25 km/s (v_d) produces enough thermal energy in the post-shock gas ($\approx$4.5 eV. per hydrogen molecule) to dissociate all the molecules.

However Dalgarno et al. (1979) show that at low pre-shock densities only a fraction of the available thermal energy goes into dissociation and higher velocities are required to dissociate all the molecules. McKee and Hollenbach (1980) found velocities $\approx$50-55 km/s for $n_0 \leq 10^3$ cm^{-3}. The studies of Draine (1980) and Draine et al. (1983) have revealed a strong dependence of v_d on the magnetic field in such a way that if this is not correctly evaluated a good estimate of molecular abundances it is impossible. The presence of the magnetic field can strongly substain the shocked material and substantially increase v_d. Anyhow nondissociative shocks mainly heat the ambient molecules and create new molecular abundance ratios by effects of increased post-shock density and temperature on the formation rate of key molecules. Dissociative shocks destroy pre-existing molecules but re-form them in the cooling post-shock gas. Orion molecular cloud is perhaps the most convincing evidence of shocked interstellar molecular gas. Occasionally, enhanced CO brightness temperature is observed behind the presumed shock front as well as increased column densities (Elmegreen and Moran 1979, Kutner et al. 1979). <u>Evidently the molecular content of a star-forming cloud is a complicated function of a variety of environmental factors</u>. Variations in the abundances of dust and heavy elements can make the molecular contents and temperatures different from the local values. Magellanic irregular galaxies, for example as we have just seen, have relatively low metal and dust abundances, and the star-forming clouds in these galaxies have relatively weak CO emission (Elmegreen et al. 1980, Tacconi and Young 1984). Such variations can make the determination of cloud properties difficult or impossible, unless all of factors that drive the abundance and excitation of the molecules used for cloud diagnostics are known for each region. A comprensive theory of star formation must be based on observations of both molecular and atomic gas in clouds that are found in different types of galaxies and in different environments of our own Galaxy.

Molecular mass distribution and GMC properties

There has been a strong uncertainty about the location in the galaxy and the origin of the GMC. Scoville and Hersh (1979) considered that these are uniformely distributed in the disk, both in arm as in interarm regions, with a lifetime of about 10^8 years; Blitz and Shu (1980) instead estimated that GMC were assembled in arm zones with a lifetime about ten times smaller. The formation mechanism was the Parker instability or the collisional growth from HI clouds (Blitz and Shu 1980). Now it is generally accepted that the GMC are confined to the spiral arms and probably the first mechanisms for their creation are density waves (Casoli and Combes, 1982; Turner 1984, Elmegreen 1986, Elmegreen, 1986 preprint).

The structure of GMC is not uniform: they appear to be constitued by several clouds of lower mass, SMC, by HI and warm gas. Casoli et al. (1984) observing large regions of galactic spiral arms corresponding to large molecular complexes in Perseus arm and Orion arm in the purpose of studing the mass distribution, counted about 300 clouds having masses ranging from 10 to $2x10^5$

Mo. They conclude, from large scale millimetric observations (mainly CO and ^{13}CO lines) that a complex and turbulent nature of molecular material is common. A hierarchy exists between molecular clouds, large molecular complexes containing smaller clumps so that one can interprete them as interwinned turbulent eddies of all sizes just as Larson (1981) finds from a sample of interstellar objects with mass in the range between $0.5-10^6$ Mo. It is not clear what entities are independent, the virial theorem is approximately verified for clumps and for large complexes, as discussed also by Larson (1981). This hierarchy is also found for sizes and velocity widths (Casoli et al. ,1984), within the large uncertainty affecting these parameters. These aspects need to be considered with more detail .

Giant clouds might be a short-lived association of smaller clumps. The largest cloud in their analysis has linear size of 90 pc (in the Perseus arm), the minimum size and mass are in Table 2.2 so that the explored range is an order of magnitude for the linear size and three order for the mass (for each arm). Searching a power-law relationship between cloud masses and sizes, they distribute the clouds in logarithmic mass bins. Power-law fits are very good and give an index between 2.6 and 2.8 (see Table 2.3). According to these fits, the mean density is nearly constant or slightly decreasing with sizes; the mean value for the volume density is found to be 50 $H_2 cm^{-3}$. It must be noted that this low value corresponds to an average across large defined sizes, the density inside a cloud can reach much higher values in clumps ($>10^4$ cm^{-3} in the star forming regions;

TABLE 2.2

-OBSERVATIONAL CHARACTERISTICS OF THE SAMPLING-

	$\langle M \rangle$ ($M_\odot$)	M_{min} ($M_\odot$)	$\langle L \rangle$ (pc)	L_{min} (pc)	n (H_2 cm ^{3})
Perseus clouds	3 10^3	200	13.5	8	50
Orion clouds	2.5 10^2	10	3.6	2	220
All clouds	2.6 10^3		11.6		65

TABLE 2.3

-CORRELATION BETWEEN CLOUD MASSES AND SIZES-

		Index	Mean density (H_2 cm ^{3})	Linear correlation coefficient
Perseus	Small clouds	2.77	42	0.86
	Large clouds	2.88	53	0.95
Orion	Small clouds	2.65	200	0.84
	Large clouds	2.67	190	0.99

From Casoli et al. (1984) where L represents the size defined at a level of antenna temperature T_a^*=0.3 K in the ^{13}CO line.

Elmegreen (1986) and references therein). Larson (1981) instead obtained the relation:

$$<n(H_2)\ (cm^{-3})> = 3400\ L_{(pc)}^{-1.10} \qquad (2.1)$$

where L is the cloud diameter. The mass range considered by Casoli et al. (1984) is much smaller than that of Larson and, in view of the large dispersion of Larson's data, a $n(H_2)$=const. relation could be fitted as well for these data for a small range of sites.

The power mass spectrum index is between -1.4÷-1.6.

After the normalization this function to the total molecular density in the solar neighbourhood ($0.5n_H\ cm^{-3}$, Lebrun 1984) for clouds in the mass range of 10^2 to 10^6 Mo and a scale height of 100 pc, the number density of molecular clouds becomes (Elmegreen 1986):

$$n(M)dM=10^{3.2\pm0.5}M^{-1.5\pm0.1}dM \qquad (2.2)$$

the mass being expressed in solar units and n(M) in kpc^{-2}. This flat distribution indicates that the spectrum is dominated by large clouds, contrary to the atomic cloud mass spectrum having as index -1.8 (Hobbs,1974). The power-law index in relation (2.2) is predicted by collisional models for the formation of molecular clouds (Kwan,1979; Casoli and Combes,1982): clouds can grow by mass accretion in two-body collision or cloud coalescence. At the end of the mass spectrum, giant molecular clouds have a finite life-time, they can be dispersed by the active and contagious star formation which occurs in one or several of their clumps, by HII regions or stellar winds and by SNs action. Their dispersion re-injects the mass to the interstellar medium and this is recycled either directly or through the atomic phase, towards the low mass end of the molecular cloud spectrum. There is a competition between the collisional time scale and the lifetime of the GMC, which determines the maximum mass the GMC can reach. If spiral waves concentrate the matter in arms, the density increase shortens the mean free path of the clouds and favours the formation of massive molecular complexes. A lifetime of $\approx 4 \times 10^7$ yr. is consistent with a maximum mass of $\approx 10^6$ Mo (Casoli and Combes 1982).

When a GMC is dispersed in the interstellar space some amount of energy from the newly formed stars (stellar winds, supernova exlposion, etc.) is injected in the cloud medium and balances the dissipation of energy in collisions. This energy input tends to flatten the velocity distribution too. The expected power index for the velocity spectrum is around -0.1 (Casoli and Combes 1982), quite different from the kinetic energy equipartition index -0.5, expected if collisions act alone. Casoli et al. (1984) wanted to test this prediction and tried to derive the velocity spectrum when data were available. In one field, they derived a velocity spectrum index around -0.2.

Equation (2.1) represents well the general trend of the data, except for some of the largest cloud complexes which have lower mean densities.

For a spherical cloud of mass M, diameter L and velocity dispersion σ, the kinetic energy and gravitational potential energy are respectively 1/2 $M\sigma^2$ and $\approx -2GM^2/L$ so that the virial theorem implies:

$$\sigma^2 \approx 2GM/L$$

This equation should be valid within a factor of 2 for most clouds of different shapes and degrees of central conditions. The data fit the relation (Larson,1981):

$$2GM/(\sigma^2 L) = 0.92\ L_{pc}^{0.14} \qquad (2.3)$$

which follows from two observed relations (Larson,1981):

$$\sigma\ (km/s) = 1.10\ L_{pc}^{0.38} \qquad (2.4)$$

for $0.1 \leq L_{pc} \leq 100$ and within individual clouds again, and

$$\sigma\ (km/s) = 0.42\ M(Mo)^{0.20} \qquad (2.5)$$

The observations of Casoli et al. (1984) confirm that the velocity dispersion does not seem to depend heavily on masses.

The equation (2.4) suggests that <u>all of the motions considered</u>, including those in the molecular clouds, <u>are part of a common hierarchy of interstellar turbulent motions and that they have no preferred length-scale</u>, although there may be local variations in their amplitude. The result is that the values of $2GM/(L\sigma^2)$ have no significant correlation with L and their mean value is -0.02 showing that , on average, the equation (2.1) is closely satisfied (Larson,1981). We can therefore conclude that <u>most of the regions studied are gravitationally bound and at least approximately, in virial equilibrium</u>. Most of large complexes also have lower average values of $2GM/(L\sigma^2)$; a plausible explanation is that many large molecular complexes contain comparable amounts of atomic gas whose mass is not included in M. The average density $n(H_2)$ varies from 10 cm^{-3} for the largest cloud to $\approx 10^5$ cm^{-3} for the smallest clumps, spanning the entire range from the densities of "standard HI clouds" to the densities expected for protostars. The correlation (2.1) may have implications for the origin of the observed structures, since it implies that the column density $<n(K_2)>L$ varies only as $L^{-0.1}$ and therefore is nearly independent of the size. This constancy of nL could result, for example, from one-dimensional shock-compression processes which preserve the column density of the regions in this way compressed. Another possibility might be that the optical depth plays an important role in the formation and survival of molecular clouds, and that this results in a favoured range of optical depth: the visual extinction implied by equation (2.1) varies only abuot 7^m for L=100 pc to 13^m for L=0.1 pc. Finally the same correlation could also be produced partly by observational selection effects if only a limited range of column densities can be detected by the available techniques. If the process that forms molecular clouds tends to generate structures with $nL \approx$const., and if the virial theorem also holds, this would imply $\sigma \propto L^{1/2}$, not greatly different from the observed relation (2.4) although it may be not possible to completely disentangle such effects from the processes of turbulence: since the internal motions in the clumps are almost always supersonic, these motions provide the dominant form of support against the gravity. To understand the SF process in the galaxy in fact one must stabilize the GMCs against their self-gravitation. Indeed if their average lifetime is typically a few times 10^7 yr, it would imply a SFR of $\approx$100 Mo/yr for the whole galaxy (Rana and Wilkinson 1986b) whereas the its value is probaly between 10-5 Mo/yr (Turner, 1984).

Star formation in molecular clouds: consequences of observational evidences.

Molecular-line observations are the most versatile probe of the internal properties of star-forming clouds. Moleculae are excited usually by collision, so the relative strengths of different emission-line transitions can be used to determine the local density of H_2 and the thermal temperature. Once the excitation is understood, the total emission in a spectral line gives the column density of the emitting species. The line profile gives the mean cloud velocity and velocity dispersion, and a map of the emission reveals the internal cloud structure and molecular boundary. Other cloud properties, such as the ionization fraction, can be determined from relative abundances of ionized species once the gas-phase chemistry is understood. The most fundamental information probably comes from the gas density; the relative importance of thermal and turbulent velocities during star formation is not well understood, and the ionization fraction has only a limited use for dynamic studies in the absence of direct magnetic field observations. Nevertheless, observations of molecular clouds have revealed a number of new properties of star formation, as Elmegreen (1986) summarizes:

<u>the density in the star forming part of a cloud</u> exceeds 10^3 or 10^4 molecules cm^{-3}, instead of only ≈ 10 cm^{-3}, as formerly inferred from 21-cm observations; it has led to a number of new concepts given below. The structure sometimes appears clumped, however, so the densest regions are probably immersed in a lower

density interclump medium (Norman and Silk,1980 and references therein). The high density observed implies that:

(a) HII regions have densities comparable to or lower than the molecular density in a cloud core, therefore most visible HII regions contain freshly ionized gas that is expanding away from an adjoining cloud; these are like blisters on the surface of a cloud (Israel,1978).

(b) The free-fall time is short enough to explain the simultaneous appearence of several short-lived O-type stars in a single cluster. It is also short enough to allow star formation to propagate inside a cloud, thus explaining the sequential appearence of subgroups in OB associations (Blaauw,1964; see also Sect. 3). Theory predicts that the time interval between star formation epochs should be comparable to the gravitational free-fall time in the ambient cloud (Elmegreen and Lada,1977). If the cloud density is too low, then the time needed by a second generation of stars to form a compressed region will be longer than the maximum age of the stars that drive the compression; massive stars will still drive shocks into the cloud, but the shocks will disperse before a new generation of stars can form. This was the objection raised by Dibai (1958) to Oort's (1954) theory of such propagating star formation. Dibai argued that the low value of the density thought to be present in star-forming clouds delayed the pressurized triggering of gravitational instabilities beyond the time when the pressure was available. Dibai thought that star formation propagated by the direct squeezing of preexisting dense globules (which also seems possible: see, Tenorio-Tagle,(1977); Whitworth,(1981); Larosa,(1983)), but not by the formation of new globules or clumps from shocked gas. Dibai's objiection disappeared when cloud density were observed to be high.

(c) High densities also imply that star formation in OB associations is very inefficient. For the observed mass of young stars in a typical OB association, the observed value of the gas density implies that the ratio of the star mass to the gas mass is low. It is such that most of the gas of a molecular cloud does not form stars at all: the clouds are either dispersed before much of the mass can change into stars, or they are delayed or prevented from collapsing by the internal pressures, turbulence or magnetic fields for a time larger than the free-fall time . The solution to this problem appears to be a combination of two effects: (i) low star formation efficiency resulting from effective cloud dispersal (efficiencies of 0.1% to 1% are likely for OB associations and of 20%-40% for OB clusters) (Duerr et al. 1982); and (ii)cloud support that delays the free-fall collapse in the core for perhaps 3 free-fall times. This factor comes from the observation that molecular self-absorption in optically thick line profiles is sometimes redshifted by about 30% of the line half-width (implying contraction of a cool envelope onto a warm core). Since line half-widths are tipically virial velocities for the cloud cores (Larson,1981) the turbulent crossing time equals approximately the free-fall time. Thus the observed redshift implies a contraction time of about 1/0.3=3 free-fall times. Other clouds studied by Myers (1980) appear to be contracting at the free-fall rate onto thermal-pressure supported cores. Giant cloud envelopes could possibly resist self-gavitational collapse because of the support from magnetic pressure and Alfvèn waves for a much longer time given by:

$$\tau_{diff} \cong 4x10^6 \; R^{1/2} \; x_7^{\;1/2} \; yr \qquad (2.6)$$

Here we refer to a cloud radius R in pc and ionization fraction x (in unit of 10^{-7}). The turbulence, if not feeded, decay more rapidly within about a free-fall time (Turner, 1984).

d) High densities and low efficiencies in star-forming regions may explain the expansion of OB associations. When a GMC is dispersed after inefficient star formation, very little of the total mass remains to bind the embedded star cluster together (Hills, 1980; Duerr et al., 1982). The cluster then expands at a velocity comparable with the velocity dispersion in the former cloud. Moving clumps inside a cloud will also scatter the embedded stars during disruption .

e) On a galactic scale, the high densities in molecular clouds imply that at least half of the ISM inside the solar circle is molecular, and that the mean density of interstellar matter is between 2 and 5 times the value formerly obtained from 21-cm observations (Solomon et al., 1979). Such high mean densities allow large-scale gravitational instabilities to grow in only $\approx 10^{7.5}$ yr, a time that is short compared to the flow-through time in a galactic spiral density wave. High mean densities also imply that self-gravitational forces exceed magnetic pressure forces from Parker instability (Elmegreen, 1982). Such gravitational instabilities may, therefore, explain how cloud and star formation is triggered in the spiral arms of galaxies that contain global density waves (Elmegreen, 1986).

Observations of gas motions suggest characteristic thermal temperatures (v.cap I) and velocity dispersion, about 5 km/s, in the star forming clouds but these observations are less significant than observations of the density, because no one yet understands what all the different types of gas motions imply. Theories of star formation often introduce a Jeans mass, which is essentially the cube of the Jeans length, $c/(G\rho)^{1/2}$ multiplied by the density ρ, but the appropriate value of the rms velocity c is not really known; i.e., should c be the thermal speed or the turbulent speed? Perhaps each speed corresponds to a different interpretation of the Jeans length, the first being the scale of a small, thermal pressure supported condensation or clump, and the second being the scale of a whole cloud. Furthemore, no one knows if the velocity dispersion is the result of systematic motions, such as contraction, expansion, or oscillation of the whole cloud, or if the dispersion derives from convection, turbulence or orbital motions of clumps. The thermal temperature can be usually explained using the known sources of heating and cooling in a cloud (Goldsmith and Langer, 1978; Evans et al.,1982), but the origin of the macroscopic motions, which are often supersonic for the observed thermal temperatures, is unknown. One apparently successful application of the thermal temperature in a discussion involving the Jeans mass has been made by Stahler (1983), who points out that the upper boundary to the location of stars on the pre-main sequence track in an HR diagram is coincident with a theoretically predicted birthline, based on a mass accrection rate for protostars that is given by the expression c^3/G (which is the Jeans mass divided by the Jeans instability time) for thermal sound speed c. This reinforces the common notion that gravitational collapse occurs within a clump of Jeans size inside a cloud of many clumps.

Internal cloud dynamics, and the dynamics of star formation, cannot be understood until molecular line profiles are explained. One of the important results to come from molecular-line profiles is the inference that nearly all stars have a strong winds at an early stage. Emission lines from the part of the cloud surrounding an embedded star often show broad pedestals from high-velocity flows (Zuckeman et al., 1976). The stellar winds are apparently pushing the ambient molecular gas away from the star (Bally and Lada, 1983).

<u>Observations of the ionization fraction</u> from HCO^+ and DCO^+, provide an estimate of the electron density in the core of a molecular cloud.

The electron density in a molecular cloud indicates how well the magnetic field is coupled to the neutral gas. The magnetic field responds directly only to the charged particles in a cloud, such as molecular and atomic ions, electrons and charged grains. Collisions between these particles and neutral atoms and molecules allow to exert a force on the bulk of the cloud, which is neutral. The ionization fractions inferred for dense molecular clouds are on the order of 10^{-7} (Langer, 1984). These fractions are high enough to allow the magnetic field to exert a significant force on the neutral matter in a cloud. Such magnetic forces can be important a) in trasferring angular momentum from a cloud core to a cloud envelope, thereby allowing the core to contract into a star without conserving the core's angular momentum, b) in the overall balance between pressure and gravity inside a cloud (Mouschovias,1979). The magnetic lines of force that emerge from a cloud can also transfer momentum from the cloud to the external gas (this reduction is about 2 or 3 order of magnitude (Larson,1984; Bodheneimer,1981)). Such magnetic connections may influence the cloud's traslational motions (Elmegreen,1981). The expression for the diffusion time , τ_{diff}, (see eq 2.6) was derived for a cloud with supersonic ion-neutral slip (corresponding to $R>1.2x_7$ pc) and a field strength that is large enough to support the cloud against self-gravity (Elmegreen,1979). Magnetic diffusion could delay the collapse of a large cloud for $\geqslant 10^7$ yr, which is long enough to explain the total duration of star formation in a typical OB association.

It must remember that the velocity needed to molecule dissociation should shifted from 25 km/s to 50 km/s in a magnetic cloud (Draine, 1980; Draine et al., 1983), so the dark clouds and GMCs or their clumps, would be much shocks-resistant than normal HI clouds.

Star formation and stellar masses

In this section I briefly summarize the general features of the star formation in our galaxy in respect to the stellar masses .

1) stars form in molecular clouds or in molecular cores.

This fact can be the effect of induced or spontaneous gravitational instability which simultaneously produces column densities large enough to molecules formation;

2) massive stars appear only in GMC ($M>10^3$ Mo) thus the star formation is drived by a bimodal mechanism.

This effect would be a selection effect produced by two different aspects:

a) these stars are statistically disadvantage to respect the low mass stars, so that in the star forming regions it is normal to found the last objects if the age are $<2x10^7$ yr with a Salpeter initial mass function;

b) if in a SMC a OB star is born, its ionizing field (or stellar wind) disruptes the cloud very rapidly stopping the star formation; this mechanism is generally accepted for the formation of OB clusters (Herbig, 1962).

3) massive stars form preferentially to the boundary of molecular clouds.

The external location of these objects suggests that external shocks trigger off the OB stars formation (Norman and Silk 1980, Franco and Cox 1983) although Silk (1978) explains it naturally as due to a global instability if the density distribution into the cloud is $\rho \propto r^{-b}$ (b>0). Then, in fact, the critical mass, for an isothermal cloud, which is given by: $M_{cr} \propto \rho^{-a}$ (a>0), (including even the magnetic cloud) becomes: $M_{cr} \propto r^{ab}$.

4) massive stars can also induce the formation of other stellar generations from shocks connected to expansion of HII regions, stellar winds or SNR: this is the propagating star formation (see the next section) .

5) it seems that massive stars form after stars of other masses are born: this is the sequential star formation (Iben and Talbot,

1966).

It is generally accepted that in the star forming regions there exists a spread in age which cannot be justified by the statistical disadvantage of the massive objects (Turner, 1984 and references therein) and that there is an exponential trend of the SFR with the mass (Iben and Talbot, 1966). However, recently Stalher (1985) has shown that these suggestions may be partly caused by a wrong age determination from pre-main sequence isochrones which is responsible for the exponential tendency of mass distribution hystogram; moreover the age determination from main-sequence isochrones which include the effects of the convective overshooting as formulated by Bressan et al. (1981) results in ages larger than "classical ages", thus reducing the spread (between turn-off and turn on) to that provided by statistical consideration (Herbig, 1962) (myself, unpublished).

6) Recently, studies of very young clusters (Sagar et al.,1986) confirm a IMF of Salpeter-type.

S E C T I O N   3.

STAR FORMATION IN GALAXIES

Introduction

In this section I will describe briefly what we know about the SFR and its history in the galaxies to look into the possible mechanisms of star formation. The SFR is produced by the simultaneous mixing of different mechanisms which act on small and large-scale, but it is unknown how these are related each other and how they depend or rather interrelate with the global properties of the galaxies.

Now it is clear that the star formation in normal spiral galaxies often operates coherently on scales of several hundred parsecs to a kiloparsec, and is sometimes associated with a total mass of 10^7 Mo or more. Even the separations between star formation sites in a galaxy give evidence for the operation of a large-scale coherent process during star formation (Elmegreen and Elmegreen 1983; Braunsfurth and Feitzinger,1985). Ionization from the largest regions can dominate the total thermal radio emission from a galaxy (Hunter, 1982) and the associated molecular clouds can dominate the total CO and infrared emission (Elmegreen, 1985). The largest HI clouds in a galaxy are often associated with these star forming regions although the atomic gas is sometimes located to the sides of the star-forming core (Viallefond et al., 1981). The evidences of large-scale structures of star formation have required theoretical interpretations and some models which can analyse and predict the consequences of this behaviour on the galactic evolution are born. This theoretical approach is generally simplified assuming a simple expression for the total SFR and reducing the number of galactic components. In this section the principal features of local and large-scale star formation are presented, moreover the available information is summarized on the relative trend of the SFR in galaxies of different type, showing that the SFR by itself can determine all the "characteristics" of the galaxies settling their Hubble types.

Small scale structures

Observations on a of about 100 pc relate at individual molecular clouds. In some clouds the formation of OB associations is an systematic ordered process which starts at one end of the cloud and proceeds in a series of consecutive separate events of star formation. There are indications that the process seems to be dominated by the propagation of ionization shocks and not by SN explosions (Lada, Blitz and Elmegreen,1979). It appears that in all the observed associations there exist a dense molecular cloud, with dimensions comparable or greater than the associations, adjacent to youngest recognizable subgroups of the association (Kutner et al., 1977; Baran,1978). These observations provide a strong supporting argument to the idea that the star formation in a massive cloud proceeds in a temporal and spatial sequence. The youngest subgroups near the molecular cloud contain the most massive and luminous stars. These vaporize the surrounding cloud creating HII regions that are ionization bound in the direction of the cloud and freely expanding in the opposite direction. The data suggest that the sequence of star formation in a gas cloud may be a very general phenomenon affecting all associations.

Further confirmation of this picture of <u>sequential star formation</u> comes from observations of the most recent star formation sites, those regions where stars have formed so recently that they are still embedded in their placental gas. These sites are indicated by water masers, compact continuum sources, CO bright spots, compact bright infrared sources, etc. The distribution of these sites is not random throughout the cloud; they are located in the surface of the cloud facing the youngest OB subgroup (Lada et al. 1979). <u>These observations suggest that the agent responsible for the onset of star formation activity is the pressure induced by the young stars themselves on the nearby gas cloud</u>.

The dynamics of the gas in this region is certainly affected by the passage of shock waves generated by the ionization fronts at the interface between neutral gas cloud and the HII region. The ambient molecular gas flows into the layer between the shock front and the ionization front and is cooled by radiation losses producing a cool dense layer where star formation may occur.

Elmegreen and Elmegreen (1978) analyzed the stability of an infinite plane-parallel bound layer and found that the cool layer is initially stable against perturbations until enough material is accumulated to allow the establishement of a gravitational instability. This is followed by a repeated fragmentation which produces fragments of the right size to form stars and smaller fragments which are too small in mass to further collapse and form stars. More theoretical work is required to clearify the physics of the compressed layers of gas. However a clear observational evidence for the cooled post shock layer situated between the expanding HII region and an adjacent molecular cloud has been obtained by Elmegreen and Moran (1979).

The high spatial resolution allowed for the observation of nearby objects in our galaxy, permits a detailed analysis of several possible consequences of the idea of propagating star formation in scales of the order of about 100 pc. The main consequence of these results is that, in order to form massive stars in a large dense molecular cloud, the process has to be triggered. This is a radical departure from the traditional picture of star formation as a natural consequence of the Jeans criterion in dense and cold gas clouds.

The idea that star formation needs a trigger was initially suggested by Opik (1953) on the basis of observations of properties of suspected SNRs. Detailed recent analyses of regions where stars have been formed in this way have reduced the list of clear candidates to three, our Solar system, the Monoceros R1 and the Canis Major R1 associations (Herbst, 1980). It is not possible at the present to unequivocally decide what actually happened. One possibility is that the SN induced the collapse of pre-existing molecular cloud, another is that the shell of material that swept by SNR in its snowplow phase was dense enough to become unstable to star formation. There is good evidence that such processes can actually occur; the best examples are the observed distributions of gas and stars in the association CMa R1 (Herbest and Assousa 1977) and Mon R1 (Jenkins et al., 1981). In both these associations one observes thin clouds that define portions of roughly circular arcs. The most recently formed stars, the ones embedded in nebulosities that constitute the R associations, are distributed along these arcs.

Large scale structures

The stellar groupings that result from large-scale star formation have been observed in many forms. The most luminous concentrations of massive stars have been termed superassociations, their sizes are of ≈ 1 kpc (Elmegreen,1985 and references therein). The formation of stars on scales from several hundred parsecs to a kiloparsec could imply either that the primordial clouds are a kiloparsec in size or that star formation continuously propagate from one generation to another.

Propagation on galactic scale was discussed qualitatively by Baade (1963) for IC 1613 and in some detailed by Westerlund and Mathewson (1966) for the LMC. More recent evidence for PSF (propagating star formation) on small and large scale has been found by Elmegreen (1985) and Table 3.1 summarizes the properties of 10 regions in which large-scale propagation should taken place. Mechanisms for propagation over distances of several hundred parsecs or more are not well understood because the obsevations are scarce. One possiility is that the pressure from a first generation of OB association pushes the ambient interstellar gas into an expanding shell, which eventually become gravitationally unstable and fragments into second generation clouds (Elmegreen, 1985). Also possible is the compression of pre-existing clouds in the region surrounding the first generation OB association (Dopita et al. 1985). The likely driving force for these mechanisms is the energy from massive stars. Regions of massive star formation

TABLE 3.1.

-REGIONS OF PROPOSED LARGE-SCALE PROPAGATION-

Region	Diameter (pc)	Propagation vel (km/s)	2nd Genetation Number	Names	Ref.
Const.III (LMC)	2000	36	18	LH51,55,60,63,75, LH76,78,79,82,83, LH86,88,91,92,95	1,2
LH77 (LMC)	2000	30	7	N51,N57,N59, N64 N63, N55, N50	3
LH85, 89 (LMC)	200	20	1	LH90	4
N158 (LMC)	180	20	1		4
Shells in LMC	100 1000	<30	5 20		5
SMC X 1 (SMC)	200	35	2	N84A, N83A	4
Origem Loop	120	20	5	S254, S258, S261 S259?, S269?	6,7
Cyg X	100	15	2	IC1318a, HSS191	8
Lindblad Ring	600	10	4	Ori OB1, Per OB2 Sco Cen Lac OB1	9,10
Mon OB2	250	20	1	Rosette Neb	11

References: 1. Westerlund and Mathewson 1966; 2. Dopita et al. 1985; 3. de Boer and Nash 1982 ; 4 Lortet et al. 1986 ; 5. Meaburn 1980; 6. Berkhuijsen 1974; 7. Pismis and Hasse 1982; 8. Dixon et al. 1981; 9. Olano 1982; 10. Elmegreen 1982b; 11 Gosachinskij and Khersonskij 1982 (from Elmegreen,1985).

receive so much energy from starlight, stellar winds and SN explosions that the local pressure can be 10 to 100 times larger than it is in the .PN53 ambient medium for a period of 10^7 years. This pressure may trigger the collapse of previously stable clouds in the vicinity, and at a same time drive an expansion of these clouds and other gas away from the association at a velocity of ≈10-50 km/s, or more. By the time the high pressure subsides, the disturbance may have grown to a radius of 100 pc or more. Thereafter the swept-up material will conserve the momentum. When the expansion finally slows dows to the local sound speed and the swept-up gas begins to disperse, the diameter of the disturbance exceed 500 pc. Disturbed regions are so large compared to the mean separation between OB associations that they may overlap, in this case OB associations would directly influence the energetics of nearly all of the interstellar matter in galaxy. Evidence for such large-scale, pressure-driven expansion is all around us, as giant loops and shells around the local OB association (Weaver, 1979; Cowie et al., 1979;1981), and as the ring of expanding gas (Lindblad,1967) centered on the old Cas-Tau association (Olano, 1982). Many other giant HI shells in our Galaxy (Heiles,1979; Bochkarev,1985) and in other galaxies (Hodge 1967; Brinks ans Bajaja,1983) and giant ring-like HII regions in the other galaxies should also have formed by pressures from young stars (Gum and de Vaucouleurs,1953; Dettmar et al.,1984).

Theoretical models

The far-reaching influence of massive star formation on ISM has led to theoretical considerations of sequential star formation

(Herbst and Assousa 1977), self-propagating star formation in galaxies (Seiden and Gerola 1986 and references therein) and self-regulated star formation (Cox 1983; Franco and Shore 1984). It has also revealed non-linear phenomena in global star formation processes and feedback control (Shore 1981, 1983; Ikeuchi et al. 1984, Struct-Marcell and Scalo 1984, Bodifee and de Loore 1985, Chiang and Prendergast 1985, Dopita 1985).

Propagating star formation leads to mutual interactions between cloud formation, star formation and cloud destruction. Non-linear models that simulate such interacting systems can be deceptively simple for some parameters, but they can exibit strong oscillations or explosions when slightly different parameters are used (Elmegreen 1985). PSF can also significantly affect the appareance of a normal galaxy. Simulations of PSF (Seiden and Gerola 1982) suggest that kiloparsec-size patches of activity should be common in galaxies, even without coherent cloud complexes to define the basic scale, and even when the propagation step size is only 50 to 100 pc. Theoretical models of such propagation show relatilvely long spiral arms, with realistic pitch angles (Scholosser and Musculus 1984) and spiral arm spurs; the high pressure cavities created in the models resemble the HI supershells observed in galaxies (Feitzinger and Seiden 1983). Brightness profiles of the model disks also match those of real galaxies (Seiden et al. 1984). These models, when the galactic disk is divided in adjacent cells of the same area and rotating in the same manner as a galaxy, depend on five parameters, the most important of them being the probability of stimulated star formation: the details of how propagating star formation is actually triggered are unknown. It is assumed that the process of triggering does take place and a parametrization is adopted in a form suitable for investigating the long-range properties of a galaxy.

Such models do not exhibit however red and symmetric spiral arms, as is observed in some galaxies; these features seem due to the action of density waves. PSF presumably operates in gaseous disks that also contain density waves (Gerola and Seiden,1979; Kaufman 1981; Smith et al., 1984). A recent extensive analysis of the observational evidence by Elmegreen (1986) indicates that for basic galactic parameters, such as SFR, colours and surface brightness, there is no significant difference between grand design galaxies (with density waves) and flocculent galaxies (without density waves). It appareas that the SF process is the same for all normal galaxies. The role of a spiral density wave is to organize the star formation already occuring into a grand design pattern as in the two-armed spiral galaxy M81 (Seiden and Gerola,1986).

The results obtained from such models have stimulated the study of the relations between local and global details of the process. Models of this type have been computed by Shore (1981, 1983), Ferrini and Marchesoni (1984), Fujimoto and Ikeuchi (1984), Bodifée and de Loore (1985) in which the component interactions have been described in a simplified manner so as to allow to a derivation of an analytic solution or a discussion of the <u>mathematical problem</u> in terms of the general analysis of non-linear systems outlined by Poincaré. In these models feedback mechanisms

are expected (as in the case of PSF (Seiden and Gerola , 1986)) however the physical mechanisms which give rise to the feedback are not well defined nor is clear if it is positive, i.e. the stars stimulate the formation of new stars, or negative,i.e the OB stars inhibit the new star generations. A more careful selfconsistent description of the ISM has been adopted by Brand and Heathcote (1982) and Ikeuchi et al. (1984) but the assumptions about the star formation process are skipping or are those by Cowie (1980, 1981) proposed in giant molecular clouds.
In this work we aim at analysing with careful detail, in the context of an evolutionary model of the ISM, some local processes of star formation arising from supersonic collisions and their dependence on the initial conditions of the medium. The assumed SFRs in fact depend explicity by the other components of the system. The purpose is to look into the reciprocal influence of the state of the ISM and the star formation and to define what different behaviour the last process can exhibit depending on the physical state of the medium. My analysis is confined, for now, to molecular clouds of intermediate-large masses ($M \leqslant 10^4$ Mo): more massive clouds confine in their interiors stars and HII regions for a large fraction of their lifetime thus making it more difficult to follow the global evolution of the ISM. Probably this simplified approach could provide useful suggestions for the treatment of the general, more complicate problem.
To compare the results it is now interesting to summarize what we know about the SFR history in the galaxies.

Star formation rate and its history

Star formation characteristics, such as the form of the IMF, and the star formation rates are recognized to play a major if not a controlling role in the evolution of the galaxies. Since it is unknown how the star formation processes interrelate with global properties of galaxies, in theoretical models of galactic evolution it is thus usual to introduce some simplifying assumptions. For example, global SFRs are often parameterized using an extended version of Schmidt's (1959) empirical description of galactic star formation rate, in which the global SFR is taken to be proportional to a power of the mean gas density (e. g. Gott 1977; Larson,1974; 1977).

With improvements in the observational facilities and techniques, empirical determinations of global SFRs are becoming available that can serve to illuminate evolutionary processes in galaxies. These have already yielded some surprises. In the Milky Way, Miller and Scalo (1979) and Twarog (1980) have found that the SFR in the galactic disk has been nearly constant over at least the last several billion years. Kennicutt (1983) has obtained similar results for an extensive sample of disk galaxies. Colors of blue galaxies also could be suggestive of nearly steady SFRs (Searle, Sargent and Bagnuolo,1973), but detailed interpretations of colors may be complicated by short-term bursts of star formation (Huchra,1977).

The existence of constant SFRs in the galaxies on the one hand suggests an underlying regularity in star formation on large scales, but on the other hand requires a theretical interpretation. For example, if we adopt the usual model in which SFR is proportional to mean density squared, then the SFR should decline precipitously in isolated galaxies as the gas supply within a galaxy is reduced by astration (see, e.g. Einasto,1972). There are, however, other classes of theoretical models that predict nearly time-constant SFRs. These include theories wherein the SFR is controlled by feedback from stars (Seiden and Gerola, 1979, 1982; Tutukov and Krugel,1981) or by gas infall (Tinsley, 1980). Further empirical exploration of the galactic star formation histories therefore can provide much-needed constraints on basic theoretical concepts. In particular, recently Sandage (1986) summarizes the properties of the Hubble sequence in past times as can be systematized by considering the time variations of the SFR following the ideas of Gallangher et al. (1984) (GHT). These authors have devised methods of estimating the SFR at three epochs in any galaxy history ($\approx 15x10^9$, $\approx 3x10^9$, and $\approx 10^8$ yr). By plotting the resulting rates as a function of time, they could show that an early-type spiral such as the Sa galaxy, NGC 2841, must have had a strongly decreasing SFR, by a factor of ≈ 10, over its lifetime so as to have produced its large bulge light and very few new stars now. Late type (Sc) galaxies with $M_T > 10^{10}$ Mo have had nearly constant SFRs. Galaxies of Sm and Irr types with $M_T < 10^{10}$ Mo have generally increasing birth rates by as much as a factor of ≈ 10 over their life-time. This SFR behaviour may suggest the parameter which drives the physics that changes the morphology along the Hubble sequence. A search for a parameter is not new (Eggen, Lynden-bell and Sandage, 1962 (ELS); Sandage, Freeman and Stokes,1970 (SFS); Larson,1972, Gott and Thuan,1976; Larson et al. 1980; Meisels and Ostriker,1984) but it seems that the work can be somewhat differently focused now due to the GHT analysis (Sandage,1986). For this purpose it is useful to emphasize that the three principal differences between Hubble early and late type galaxies are (1) the presence or absence of a nuclear bulge, (2) the presence or absence of a disk, and (3) the relative abundance of gas and very young stars in the disk. Diskless and disk system separate the entire sequence between the E and SO types, whereas the decreasing bulge-to-disk ratio and the increasing abundance of gas and young stars divide the disk sequence into the Sa, Sb, Sc, Sd, Sm and Im bins.

It was from the beginning realized (SFS 1970) that the amount of gas left over in the disk after the strong dissipative collapse in galaxies that were to become disk-like determined where along the Hubble sequence a galaxy would be initially placed. Gott and Thuan (1976) developed the idea quantitatively, identifying density-contrast rather than angular momentum (as in SFS) as the controlling factor in the crucial ratio of collapse time to the star-formation time scale.

For the diskless E galaxies it had always been clear (ELS) that stars had to be formed from the initially collapsing gas at a rate faster than the $(G\rho)^{-1/2}$ collapse time, otherwise a disk would form contrary to the observation. This immediately sets the early SFR in E galaxies at:

$$(SFR)_i \geq M_T/t_c \geq M_T\sqrt{G\rho} \text{ solar masses/ year}$$

where t_c is the collapse time and the index "i" represents the integrated quantity. Even if t_c were put as long as 10^9 yr (5 times longer than that used by ELS), then:

$$(SFR)_i(\text{E galaxies}) \geq 10^{-9} \text{ solar masses/year per Mo} \quad (3.1)$$

Because the main bulk of an E galaxy collapsed on a time scale shorter than 10^9 yr (although there is a hierarchy of times for shells at various radii, the time depending on the density of each shell), eq (3.1) is surely a lower limit. Putting $t_c=2x10^8$ yr from ELS gives:

$$(SFR)_i(\text{E galaxies}) = 5x10^{-9} \text{ solar masses/year per Mo} \quad (3.2)$$

which is ≈50 times larger than the present SFR in the solar neighbourhood. The estimate is quite general based only on the requirement that no disk form in E galaxies.

The history, of course, had to be somewhat different in SO galaxies where a high surface-brightness old disk exist in which no star formation is now taking place. In this picture, this disk together with a large nuclear bulge can be understood if the early $(SFR)_i$ was only slightly smaller for SO galaxies than in E systems. If so, although **most** of the stars are born in nondissipative phase of near free-fall before disk formation (thereby giving a great bulge), **some** gas was left over a time $>t_c$, permitting a disk to be formed by the catastrophic great dissipation of the decay of the Z energy (i.e. in direction parallel to the net angular momentum axis) due to gas hitting on the galactic plane. Nevertheless, the $(SFR)_i$ was so high in the resulting disk as to permit all remaining gas to be converted into stars within at least the last 10^9 yr (a time betrayed by the equality of colors of E and SO systems [Sandage and Visvanathan, 1978]) giving rise to the present-day impotent SO galaxies (Larson et al. 1980).

Note that the disk superface-brightness of SO galaxies is extremely high (Sandage, 1983), a natural consequence of the picture where the $(SFRs)_i$ were very high both for the spheroidal and the disk components during their initial formation periods. The story can be made the same for later-type galaxies along the Hubble sequence if the present and the initial $(SFRs)_i$ are properly adjusted to give the appropriate progressive variation of the bulge-to-disk ratio.

A rappresentation of the variation of the $(SFR)_i$ with time in E, SO, and Sa galaxies is shown in Fig. 3.1 (Sandage, 1986). What results from the diagram is that the relative rate at which gas is converted into stars differs from E to Sa galaxies and this, of course, is what gives rise to the difference in the Hubble type. To repeat the most important point (from Fig. 3.1): <u>the ratio of the time required to complete the star formation (t_s) to the collapse time (t_c) determines wheter a disk forms, and if it does, what the bulge-to-disk ratio becomes</u>.

Also shown in Fig. 3.1 is a schematic rappresentation of the difference between E0 and E6 galaxies, suggesting that the bulk of the stars in the highly flattened E galaxies must form slightly later than in true E0 systems (i.e. $(SFR)_i(E6)<(SFR)_i(E0)$), with the consequence that the more dissipation (i.e. cooling) has occured in the initial gas in E6 systems. This causes the Z energy to be partly destroyed , causing a flattening, not by rotation but by a nonisotropic velocity ellipsoid (Sandage, 1986).

Finally, it should be noted from Fig. 3.1 that the present day surface brightness of Sa disks can be expected to be lower than

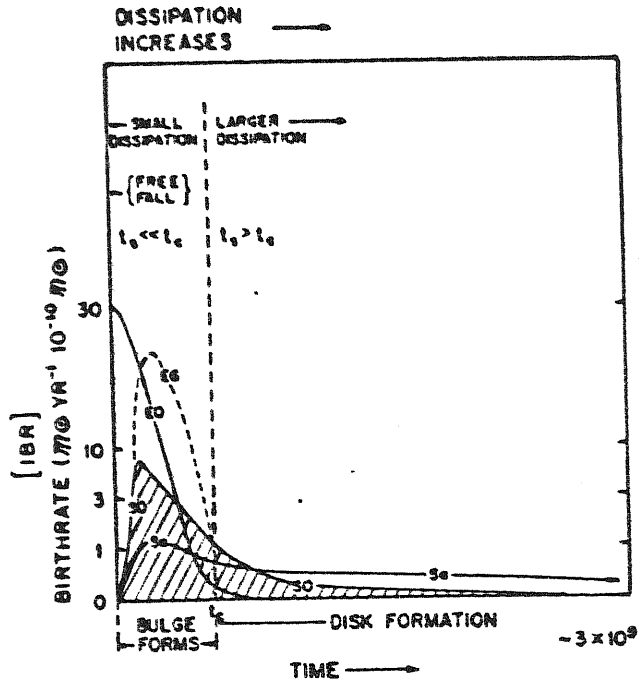


Figure 3.1

Fig. 9. Schematic representation of the change of the star formation rate with time for galaxies of types E, SO, and Sa. The dashed vertical line at the collapse time t_c separates regions of low dissipation (to the left) from those of high dissipation (to the right). Bulges form in the left region, disks in the right. The integral under the curves gives the total number of stars formed (per unit galaxy mass). The integral under the SO curve is shaded

From Sandage (1986).

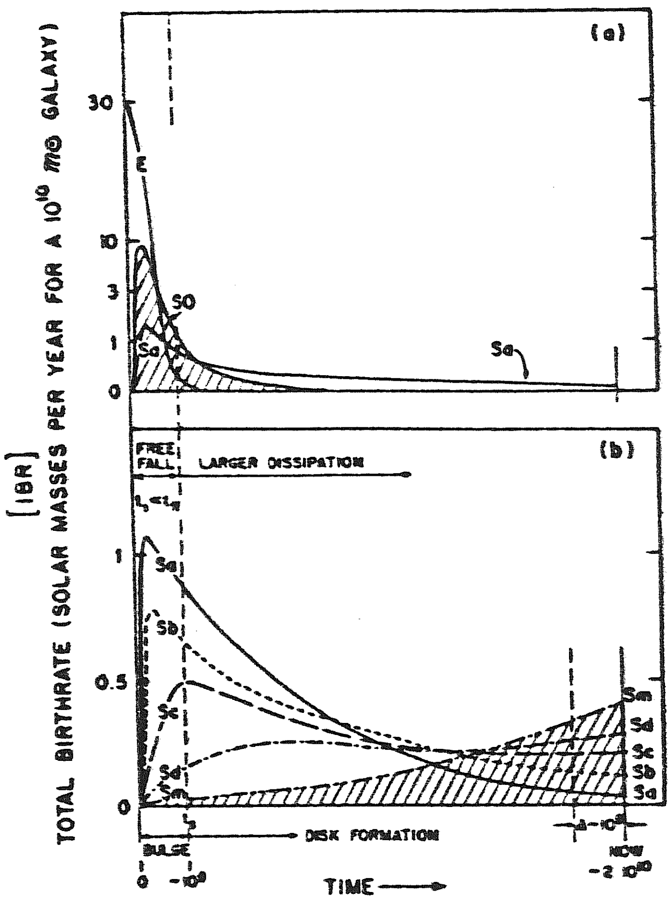


Figure 3.2

Fig. 10. Same as Fig. 9 with later Hubble types shown in the lower panel. The integral under the Sm curve is shaded for illustration. The curves are only schematic showing the trends that have been established by Gallagher et al. (1984)

those in SO disks of the same mass because gas still does exist in the Sa's, yet to be converted into stars, whereas all such gas that was in the SOs is now already in stars. Observation confirms this expectation (Sandage, 1983).

Fig. 3.1 is repeated at a different scale in the upper panel of Fig. 3.2, and is generalized for the later Hubble types in panel b. Again, the crucial vertical line is shown which separates the epochs of bulge and disk formation at the collapse time, t_c.

The feature of Fig. 3.2 to be noted are:

(1) the <u>differences</u> in the integrated birth rates between Sa, Sb, Sc, Sd, and Sm types during the time $t<t_c$ of bulge formation determine the bulge sizes of these galaxies.

(2) The ratio of the integrals under each curve to the left and to the right of the vertical t_c line determines the bulge-to-disk ratio.

(3) The integral under the curve to right of the vertical line, extended to the present epoch, determines the present surface brightness of the old disk. For illustration, this integral under the Sm curve is shown.

(4) The intersection of each curve with the vertical line marked "now" shows the <u>present</u> (SFR) for each Hubble type (each curve to be normalized to the mass of the given galaxy).

(5) The ratio of the integral under each curve in the time interval labeled $\Delta\approx10^9$ at the lower-right edge, to the integral from time t_c to ($t-10^9$ yr) gives the relative color of the integrated light. Young stars appear only in the $\Delta\approx10^9$ region: old disk stars (ages $>10^9$ yr) are to the left.

The Fig. 3.2 seems capable of explaining the five principal observational facts concerning the Hubble sequence:

(1) the bulge-to-disk ratio is a function of Hubble type;

(2) the disk surface brightness varies systematically with Hubble type;

(3) integrated colors varies systematically with bulge-to-disk ratio and with the Hubble type;

(4) the mean age of the disk is a function of Hubble type;

(5) the present (SFR) (per unit mass) for Sc galaxies is much larger than for SO and Sa galaxies.

But interesting as Fig. 3.2 may be as a summarizing device, it contains no physics. The next step is to identify the driver that controls the ratio of the star formation rate (SFR) to the collapse rate, and therefore controls the amount of gas left over in the disk after dissipation. Tully, Mould and Aaronson (1982; also Tully, 1983) suggest that mass alone determines the Hubble type, but this is not a complete identification of the driver because the mass range of galaxies of all Hubble types earlier than Sd overlap one another (Rubin 1983): there are Sc galaxies of the same mass as Sa's.

Sandage et al. (1970) identified the driver to be the angular momentum per unit mass, observing that in regions of high angular momentum, star formation is generally inhibited (Mestel, 1985a, b). Gott and Thuan (1976) consider the density as the parameter because $\rho^{-1/2}$ determines the collapse rate and some other power of ρ may control the SFR.

Future observations may isolate the parameter which we need but which we have not yet singled out. One could believe that precise measurements with high spatial resolution of say the absolute surface density (Silk 1985) in the bulges and disks of galaxies of all the Hubble types, compared at a suitable defined "equivalent radius", might provide the needed insight (Sandage, 1986) .

S E C T I O N 4.

THE MODEL DESCRIPTION

Introduction

In this section are presented the fundamental assumptions of my model. This is a multicomponent selfconsistent one zone model which contains a simple formulation of the star formation processes depending explicity on the other components of the model. The aim is to examine if the physical state of the several components is able to affect one other and in particular the star formation rates.

Basic assumptions of the model

The system consists of six components:

1) HI clouds, 2) H_2 clouds, 3) ambient gas or the intercloud medium (ICM), 4) shells of SNRs, 5) hot cavities of SNRs, 6) star component.

The interchange processes between these components are the following:

a) sweeping of the ambient gas by the expanding SNRs; this swept gas feeds both the hot cavities and the cool shells;

b) photoionization of clouds by the radiation field produced by young hot stars and SNRs, this process feeds the ambient gas;

c) gravitational instability of the shells of those remmants which have ended their expansion, ensuing fragmentation and formation of HI clouds.

d) mixing with the ambient medium of the gas into the hot cavities, when their shells break up. It is assumed that: the temperature of such gas is $3x10^5$ K, the mixing is instantaneous and the resulting temperature is the average of the two components which mix;

e) evaporation of the clouds embedded in the hot cavities;

f) formation of molecular clouds by collision and coalescence of HI clouds;

h) mass loss from stars: the gas set free is mixed with the ambient medium.

For both types of clouds a monochromatic mass spectrum has been adopted; the main reason for this choice is to avoid further computational complications; moreover the mass spectrum, instead of being considered an input datum, should be rather an outcome of the model (Chièze and Lazareff 1980): this however would require the introduction of further parameters and hypotheses. The processes listed under a),c),d) and e) have been treated as in Habe et al. (1981). The parametrization of the evolution of SNRs has been in fact derived according to their scheme (in my thesis) however a different evaluation has been adopted for the length of the adiabatic phase according to the suggestion of Hollenbach and McKee (1979) and McKee and Hollenbach (1980): this length, τ_2 is now equal to $5.3\times10^3 n_a^{-0.63}$ yr where n_a is the ambient density. According to Cowie and McKee (1977) and McKee and Cowie (1977) a shortening of the length of the adiabatic phase, similar to that resulting from the above mentioned relation, is consequent on thermal conduction. With this new definition of τ_2, the time required for the attainment of the steady state of the ISM in the models of Habe et al. (1981) would be doubled. For the adopted values of cloud radius, evaporation is the only possible phenomenon for clouds embedded in hot cavities of SNRs with $\tau<\tau_2$, the condensation being negligible.

Process f) of formation of molecular clouds through coalescence of HI clouds is described by the term:

$$dM_{c_2}/dt = M_{c_1}/\tau_{c_1} \qquad (4.1)$$

τ_{c_1} being the lifetime of the HI clouds against collisions, given by:

$$1/\tau_{c_1} = (dn_{c_1}/n_{c_1}dt) = 1/(n_{c_1}\pi R^2_{c_1}v_r) \qquad (4.2)$$

n_{c_1} being the number density of clouds, R_{c_1} and v_r respectively the radius and the relative velocity.

<u>The stellar component</u>

The assumptions about the stellar component are the following: a) the initial mass function $\phi(m)$ is of the Salpeter type with an exponent $\alpha=-2.5$ and the mass range is (0.01-100)Mo; b) the stars have been subdivided into two categories: <u>massive stars</u> ($m\geq10$Mo) which are supposed to end their evolution with a supernova explosion and during the Main Sequence phase emit the ionizing radiation which excites the HII regions and <u>low mass stars</u> ($m<10$ Mo) which are assumed to evolve without giving rise to supernovae (in this way type I supernovae are neglected). This subdivision is justified by the fact that only the more massive stars strongly interact with the other components and are responsible for the production of the SNRs and of the ionizing field (the contribution to the last one from other types of objects, such as for instance nuclei of planetary nebulae, is negligible, see Salpeter (1979)). The role of less massive stars, apart from their passive function subtracting matter from the clouds in the formation process , is limited to feeding the ambient medium through the mass loss. Therefore, while these two effects are included respectively in the equations for the cloud components and in that for the ambient medium, only the equation for the massive stellar component (m>10 Mo) is explicitly present in the system. This is of the type:

$$dM_s/dt = (dM_s/dt)_{sf} - (dM_s/dt)_d - (dM_s/dt)_{ml} \qquad (4.3)$$

where M_s is the total mass of these stars; the first term at the right member represents their star formation, the second gives the death and the third accounts for the mass loss. Interpolation of the evolutionary computations of Chiosi et al. (1978) yields the average rate of mass loss of a massive star as a function of its original mass:

$$\dot{m} = 5.6\times10^{-11}M^{2.66} \quad Mo/yr \qquad (4.4)$$

the arithmetic mean of this quantity, weighted over the initial mass function, gives the average rate of mass loss for the group of massive stars: $<\dot{m}>=1.2\times10^{-6}$ Mo/yr. Then we assume:

$$(dM_s/dt)_{ml} = <\dot{m}>/<m>\ M_s \qquad (4.5)$$

where $<m>$ is the mean original mass of massive stars: $<m>=21.2$ Mo.

The term $(dM_s/dt)_d$ has been expressed by the relation:

$$(dM_s/dt)_d = (M_s/<t>)\{1-(m_r/<m'>)\} \qquad (4.6)$$

where $<t>$ is the average lifetime and has been evaluated from the data shown in Table 2 of Chiosi and Maeder (1986, preprint) and from the initial mass function: the value of <t> is $1.02x10^7$ yr; evolutionary phases beyond core He-burning have been neglected as they do not contribute appreciably to the total lifetime; m_r is the mass of the remmant, left after the supernova explosion, to which a value of 2 Mo has been assigned; <m'> is the mean value of the final mass before supernova explosion which is evaluated, taking into account the mass loss, in a way similar to that for <m>.

The term $(dM_s/dt)_{sf}$ is related to the total star formation rate (SFR) ψ by:

$$(dM_s/dt)_{sf} = [\int_{10}^{100} m\phi(m)dm / \int_{0.01}^{100} m\phi(m)dm] = .0218\psi \qquad (4.7)$$

The evalutation of ψ is discussed in the next point.

The supernova rate per unit volume is given by:

$$r_{SN} = M_s/(<m'><t>\ V) \qquad (4.8)$$

where V is the volume of the system.

The photoionization rate of the clouds, ζ, which is the mass fraction of a cloud, ionized per unit time, depends on the field produced by stars and SNRs. As the number of the last mentioned is roughly proportional to the number of massive stars present, we set:

$$\zeta = \sigma\ M_s \qquad (4.9)$$

the value of the constant σ can be determined from the data used by Habe et al. (1981): $\zeta=10^{-16}$ sec^{-1} when $r_{SN}=10^{-13}$ $yr^{-1}pc^{-3}$.

From (4.8) and (4.9) one derives then $\sigma=1.46x10^{-13}$ $Mo^{-1}yr^{-1}$.

The photoionization of the clouds is given by:

$$dM_{c_1}/dt = -\sigma M_s M_{c_1} \qquad dM_{c_2}/dt = -\sigma M_s M_{c_2} \qquad (4.10)$$

where M_{c_1} and M_{c_2} are respectively the total masses of HI and molecolar clouds.

The process h) of feeding of the ambient gas by the mass lost by stars is quantified by the relations (4.2) and (4.3) for massive stars; for low mass stars the instantaneous recicling approximation is not correct and the following relation instead must be used:

$$(dM/dt)_{ML} = \int_{\mu}^{10} \alpha(m)\phi(m)\ m\ \psi(t-\tau_m)dm \qquad (4.11)$$

where $\alpha(m)$ is the fraction of stellar mass returned to the ambient medium (Talbot and Arnett, 1971) which we assume lost at the end of the life of the star whose length is τ_m; μ=min(10;m(t)) with m(t) the mass of that star whose lifetime is t.

<u>The processes of star formation</u>

The mechanisms here considered are those related to shocks induced by collisions between molecular clouds and other components of the system; on the contrary I neglect density wave shocks which do not seem strong enough to start gravitational instability (Elmegreen 1986). In some models a mechanism of spontaneous formation has also been introduced, connected with the decay of turbulence (Turner 1984).

In the following I briefly analyze the rate of these processes.

1) Cloud-cloud collisions (c-c process)

It is assumed that, when two molecular clouds collide, there is some finite probability that they become gravitational unstable and some fraction of their mass is converted into stars. The amount of gaseous mass which is transformed into stars per unit time is expressed by:

$$\psi_1 = 0.5 \times n^2_{c_2} \sigma_1 v_r V \, 2 \, m_{c_2} \eta_1 \qquad (4.12)$$

where $n_{c_2} = M_{c_2}/(m_{c_2} V)$ is the number density of molecular clouds, m_{c_2} the mass of each cloud, σ_1 the geometrical cross section: $\sigma_1 = 2\pi R^2_{c_2}$, R_{c_2} being the radius and v_r the relative velocity, whose value is taken to be 10 km/sec; η_1 is a parameter which depends on the geometry of the collision and on the physical behaviour of the shocked material and can be adopted as a measure of the efficiency of the process.

Equation (4.12) may be written in the form:

$$\psi_1 = A \, M^2_{c_2} \qquad (4.13)$$

with $A = 2 \pi R^2_{c_2} v_r \eta_1 / (m_{c_2} V)$.

2) Collisions between clouds and shells of HII regions (c-h process)

The rate of this process can be expressed by:

$$\psi_2 = n_{c_2} n_{sh} \sigma_2 v_r V m_{c_2} \eta_2 \qquad (4.14)$$

where n_{sh} is the number per unit volume of HII regions which have developed a cold shell, $\sigma_2 = \pi(R^2_{c_2} + R^2)$ is the geometrical cross section and R the radius of the ionized region. The parameter η_2, as in the previous case, is the efficiency . According to Elmegreen (1978) only the clouds become gravitational unstable and therefore the maximum mass at disposal for the star formation is the cloud mass.

For n_{sh} we assume:

$$n_{sh} = (M_s/\langle m\rangle V)\langle\Delta\tau(m)/\tau(m)\rangle \tag{4.15}$$

where $\Delta\tau(m)/\tau(m)$ is the lifetime fraction of a star of mass m, during which the HII region, by it excited, exhibits the shell and $\langle\Delta\tau(m)/\tau(m)\rangle$ is the average value for massive stars. A reasonable guess for this quantity is 1.

The radius R of the ionized region can be approximated by the Stroemgren radius (Spitzer 1978):

$$R = [\ 3\ S_o/(4\ \pi\ n_e n\ \alpha]^{1/3} \tag{4.16}$$

S_o is the number of ultraviolet photons emitted from the exciting star per unit time; it is a function of stellar mass: for the adopted initial mass function the average value of S_o is 2×10^{48} sec^{-1} and this value has been used in (4.16); α is the hydrogen recombination coefficient . If we ignore the ionization of helium the electron density n_e is equal to the hydrogen density; moreover we can approximate $n \approx n_a$.

The rate (4.14) can be set in the form:

$$\psi_2 = B\ M_{C_2} M_s n_a^{-4/3} \tag{4.17}$$

where:

$$B=\{\pi\ v_r\ \eta_2/(\langle m\rangle\ V)\}[\ 3\ S_o/\ 4\ \pi\ \alpha\ ]^{1/3} \tag{4.18}$$

Also in this case for the relative collision velocity we adopt the value of 10 km/sec since the expansion velocity of a HII region ranges between 1 and 10 km/sec. From (4.17) turns out that the rate is controlled by the conditions of the ambient gas through the factor $n_a^{-4/3}$.

3) <u>Collisions between clouds and shells of SNRs</u> (c-s process)

Responsible for this process are the expanding SNRs with a cool shell, that is to say, those remmants whose age is between τ_2 and τ_3 (τ_3 marks the end of the expansion phase).

The rate is:

$$\psi_3 = \int_{\tau_2}^{\tau_3} n_{c_2} n_{SNR}(\tau)\ \sigma_3 v_r V\ m_{c_2} \eta_3 d\tau \qquad (4.19)$$

where $n_{SNR}(\tau)$ is the number density of remmants of age τ. Clearly $n_{SNR}(\tau)\propto r_{SN}(t-\tau)$ where t is the present age of system; $\sigma_3=\pi(R^2_{c_2}+R^2(\tau))$ is the cross section and $R(\tau)$ the radius of a remmant τ years old; v_r is the relative velocity and, provided that the expansion velocity of the remmant is, for the majority of its lifetime, considerably larger than the clouds velocity, we can approximate v_r with $dR/d\tau$.

Neglecting in the cross section $R^2_{c_2}$ compared with $R^2(\tau)$ and setting $r_{SN}(t-\tau)\approx r_{SN}(t)$, which is a reasonable approximation since τ_3 is small compared with the time-scale for a significant change in the stellar birth-rate, we derive from (4.19):

$$\psi_3 = C\ M_{c_2} M_s \qquad (4.20)$$

with:

$$C=[\pi R^3(\tau_3)/(3\langle m\rangle\langle t\rangle V)]\eta_3=3.02\times10^7 n_a^{-1.11} T_a^{-.6}(\langle m\rangle\langle t\rangle V)^{-1}\eta_3 \qquad (4.21)$$

where the expressions of $R(\tau)$ and τ_3 as functions of n_a and T_a have been used. The rate of this process, too, depends on the conditions of the ambient gas, although weakly by its density.

The η_i parameters

The introduction of the parameters η_i in the rates now analyzed is the consequence of the inability of adequately describing the behaviour of the shocked material; the outcome of the collisions can be various (coalescence with gravitational instability, coalescence only, partial coalescence, disgregation, etc.) depending on several factors: density and dimensions of the colliding objects, collision velocity, impact parameter and thermodynamic properties of the gas. An overall treatment of this phenomenon is still lacking and therefore general rules are not available. Partial and approximate approaches have been presented by several authors (Stone, 1970; Smith, 1980; Chièze and Lazareff, 1980; Hausman, 1981; Struck-Marcell, 1982; Gilden, 1984). Gilden's results for head-on collisions between identical clouds or clumps show that the probability of coalescence followed by gravitational instability is high even if the mass of each colliding objects is smaller than Jeans' mass. Collisions of identical objects with Mach number near to 1 or between objects with different mass result in coalescence but the probability of collapse is very small.

An analysis of the time-scales involved can help however in singling out some of the physical quantities which can affect these efficiencies and in reducing the number of parameters.

According to Elmegreen (1978) a necessary condition for shocks to produce star formation is that the length of the compression phase t_{comp} is long enough to prevent the reexpansion of the cloud and allow the full establishment of the gravitational collapse. This requirement is expressed by the condition $t_{ff}<t_{comp}$: where t_{ff} is the free fall time. The efficiency of the star formation depends therefore on the ratio t_{comp}/t_{ff}: the larger this ratio the larger the efficiency. We can write:

$$\eta_i = \eta_i'(t_{comp}/t_{ff}) \tag{4.22}$$

with (i=1,2,3). In the case of collisions between clouds t_{comp} is the time required for the shock to cross the cloud: $t_{comp}=t_R=2\ R_{c_2}/v_r$; in the two other cases $t_{comp}=\max(t_R;t_{sh})$ where t_{sh} is the lifetime of the shock; for a HII region and for the adopted parameters of the clouds it turns out $t_{comp}=t_{sh}$ while in the case of a SNR shock $t_{comp}=t_R$, since the lifetime of the shell is very small.

In the following we assume that the coefficients η_i', which depend on possible magnetic fields, velocity collision, cooling mechanisms, characteristics of fragmentation, are independent of the nature of the colliding objects and therefore have the same value η' for all the three processes. In the c-s case, the collision velocity is larger than in the other two cases: to have assumed that η_3' has the same value as η_1' and η_2' is only justified by the fact that the c-s process, notwithstandig this, a posteriori turns out much less important than the other two.

Critical analysis of the assumptions concerning star formation

In this section I want to compare some of the assumptions previously introduced with the present knowledge of the star formation process (see also Sect.2 and 3).

The main points are:

1) the formation of giant molecular clouds has been a controversial argument for a long time; there seems to be now a wide agreement that coalescence only from random collisions requires too large a time in order to build up the observed mass spectrum of clouds. According to Turner (1984) and Elmegreen (1986) molecular complexes form through density wave shocks;

2) the majority of molecular clouds are in equilibrium even if their mass is widely larger than Jeans' mass: gravitational forces are balanced, for time intervals longer than the free-fall time, by the turbulence, whose source against dissipation could be the differential galactic rotation (Turner 1984). The turbulence, which is supersonic, decays with a cascade as is suggested by Larson (1981) and Myers (1983) who derived a relation $\Delta v \propto R^{\kappa}$ $(0<\kappa<1)$ between the velocity dispersion Δv and the dimension of the region concerned. This decay gives rise to hydrodynamic instabilities and formation of subcondensations of smaller dimensions until, according to the previous relation, turbulence in them becomes subsonic: they become decoupled and undergo gravitational collapse giving rise to stars of low mass. Such stars probably have been formed since the beginning of the cloud life;

3) massive stars are produced only when two conditions are

fulfilled: a) the formation within the cloud, by accretion or by concentration of gas, of clumps massive enough (Turner 1984); such massive clumps can form only in giant clouds ($M>10^3$ Mo); b) clumps become unstable by an outer shock: those arising from collisions of clumps with clumps, shells of HII regions and SNRs are effective in starting the collapse. Therefore in the large molecular clouds low mass stars form from the beginning, while massive stars are produced only when conditions a) and b) are met.

Since only half of the giant molecular clouds show OB stars, it can be presumed that the requirements for the formation of massive stars are reached only after about half of the cloud lifetime $\approx 2\times10^7$ years; 4) the formation of massive stars develops the conditions for the disgregation of the parent cloud through the action of HII regions, SNRs, whose combined energy release is larger than the binding energy of the clouds. Times of the order of a few million years are required.

Let us compare with this scenario the following made assumptions:

(1) <u>formation of molecular clouds</u>. It has been supposed that molecular clouds form from random collisions of HI clouds; since the adopted mass of molecular clouds is intermediate, the formation time by collision can be reasonable. Consequences of this choice on the evolution of the system will be analysed in Sect.5.

(2) <u>mass of molecular clouds</u>. The mass adopted for the molecular clouds is constrained by two requirements: a) within each cloud a stellar generation must be formed with at least one massive star capable of disgregating the cloud with its HII region and/or SNR.

With the adopted initial mass function and provided that the probability of formation of a star is independent of its mass, only 10% of the cloud material is converted into stars (Elmegreen 1983) a minimum cloud mass of 4000 Mo is found; b) an upper limit to the cloud mass can be set by imposing that HII regions and SNRs, produced in it, evolve for most of their lifetime in the ambient gas and not in the cloud. This condition is satisfied for a mass of 10^4 Mo, as will be shown when discussing the cloud disgregation.

(3) <u>duration of star formatiom process and disgregation of clouds</u>. It is assumed that the whole process of star formation starts after the cloud has been struck by a shock then the birth of low mass stars is delayed by an interval less then 10^7 yr. Since the main influence these objects exert on the ISM is the gas restitution during the advanced phases of their evolution, such a delay is unimportant compared with their lifetimes.

It is also assumed that the cloud disgregation follows immediately the star birth and consequently HII regions and SNR's expand in the ambient medium, not in the clouds. This approximation also seems correct as it results from Table I which presents the time required for the erosion of a cloud of 10^4 Mo by a HII region excited by a single star of given mass, for different cloud densities. A single HII region is capable of disgregating a 10^4 Mo cloud in a time interval equal to about one tenth of its lifetime.

Table I.

Erosion time t_{er} of a cloud of 10^{4} Mo and density n_0 for two different exciting stars.

M = 30 Mo	OB star	M = 15 Mo	BO star
$t=8x10^{6}$ yr.	$S_0=2.4x10^{49}$ sec^{-1}	$t=1.4x10^{7}$ yr.	$S_0=7x10^{47}$ sec^{-1}
$n_0=10^{2}$ cm^{-3}	$t_{er}=7.4x10^{5}$ yr.	$n_0=10^{2}$ cm^{-3}	$t_{er}=1.8x10^{6}$ yr.
$n_0=10^{3}$ cm^{-3}	$t_{er}=6.1x10^{5}$ yr.	$n_0=10^{3}$ cm^{-3}	$t_{er}=1.5x10^{6}$ yr.

t is the main sequence lifetime and S_0 the UV photon flux.

S E C T I O N 5.

RESULTS

Introduction

In this section and in the next one are presented the models obtained by solving the system of the equations previously described, for different values of the initial conditions and of some parameters as η', R_{c_2}, and the constant σ related to the photoionization of the clouds. Other models have also been computed in which some of the basic assumptions have been changed in order to test their influence on the results.

The standard model

As a reference we take the model A1, whose initial conditions and parameter values are listed in Table II: the quantities shown in this Table change from model to model while the following ones have been kept constant in all the models: mass of each molecular cloud $m_{c_2}=10^4$ M☉, mass and radius of each HI cloud $m_{c_1}=100$ M☉ $R_{c_1}= 2$ pc respectively, initial temperature of the ambient gas $T_a=10^4$ K; the total masses of the components other than the molecular clouds and the ambient gas are initially zero.

The value of η' for the model A1 and the other models is rather arbitrary: the efficiency η_i can be tought of as the product of two factors ε_{i_1} and ε_{i_2} where ε_{i_1} is the probability that a collision results in a gravitational collapse and ε_{i_2} is the fraction of the cloud mass which is converted into stars; ε_{i_2} is of the order of 10^{-3} as is derived for the efficiencies of star formation in molecular clouds (Elmegreen,1983); due to the lack of a suitable theory of supersonic collisions it is impossible to give an estimate for ε_{i_1}: we can only set $\varepsilon_{i_1}<1$. Since that

Table II.

List of the models and their parameters.

Model	$M_{C_2}(0)/M_\odot$	$n_a(cm^{-3})$	η'	$\sigma(yr^{-1}\ M_\odot^{-1})$	$R_{C_2}(pc)$
A1	$8x10^7$	0.028	$2.65x10^{-5}$	$1.5x10^{-13}$	4.3
A2	$8x10^7$	0.028	$1.30x10^{-4}$	$1.5x10^{-13}$	4.3
A3	$8x10^7$	0.28	$1.30x10^{-4}$	$1.5x10^{-13}$	4.3
A4	$8x10^8$	0.028	$2.65x10^{-5}$	$1.5x10^{-13}$	4.3
A5	$8x10^6$	0.028	$2.65x10^{-5}$	$1.5x10^{-13}$	4.3
A6	$8x10^7$	0.28	$2.65x10^{-5}$	$1.5x10^{-13}$	2.0
A7	$8x10^7$	0.28	$2.65x10^{-5}$	$1.5x10^{-13}$	4.3
A8	$8x10^7$	0.028	$2.65x10^{-5}$	$1.5x10^{-14}$	4.3
A9(*)	$8x10^8$	0.028	$2.65x10^{-5}$	$1.5x10^{-13}$	4.3
A10(**)	$8x10^8$	0.028	$2.65x10^{-5}$	$1.5x10^{-13}$	4.3
A11(***)	$8x10^7$	0.028	$2.65x10^{-5}$	$1.5x10^{-13}$	4.3
A12(****)	$8x10^7$	0.028	$2.65x10^{-5}$	$1.5x10^{-13}$	4.3

(*) including spontaneous star formation with $t_{sp}=10^9$ yr.

(**) including spontaneous star formation with $t_{sp}=10^8$ yr.

(***) the time scale for formation of molecular clouds is $\tau_{C_1}=10^7$ yr.

(****) the supernova rate is icreased articially by a factor of 5.

t_{comp}/t_{ff} is in the range 1÷10, from (4.22) we derive $\eta'<10^{-2}$: probably η' is much lower than 10^{-2}. For the adopted value of η' a time of several billion years for the active phase of star formation ensues.

In Figures 5.1a and 5.1b the evolution of the birth-rate is shown for model A1. One can single out a short initial phase, whose length is about $2x10^7$ years, characterized by a continuously increasing birth-rate.

As the mass of the stellar component is zero, initially only the c-c process is active, but soon, as the first generation of massive stars begins to excite the HII regions, the c-h process becomes more and more important so that prevails. However a necessary condition for the establishment of the new regime of star formation is that the ambient density n_a is initially sufficiently small or progressively decreases below a critical value, $(n_a)_{cr}$. This aspect can be easily ascertained by solving the equation of the stellar component under the assumption that the cloud mass is constant, as it results from the models for this first phase. In fact the solution of the massive stars component which satisfies the initial condition $M_s(t_0)=M_{s0}$ is:

$$M_s=M_{s0}\exp(K\ \Delta t)+(A\ M_c^2/K)(\exp(K\ \Delta t-1)) \qquad (5.1)$$

with:

$$K=B\ M_c\ n_a^{4/3}-R = \text{const.}$$

If n_a is large enough then K<0 and M_s tends to decrease showing that, in such way, the c-h process cannot prevail. If on the contrary the density is small and therefore K>0 M_s will increase with the time and at some instant this process will become dominant.

After a maximum the birth rate shows a phase of quasi-steady state or of slow decline lasting about 10^9 years, this is a phase of very active star formation.

The stop of growth of ψ is the consequence of a small increase of n_a which affects the rate of the dominant process according to the relation (4.17). In turn the increase of n_a is due to the temporary prevalence of the feeding mechanism, namely the photoionization.

The subsequent decline of the SFR arises from the consumption of the intercloud medium due to the sweeping of SNRs; there are two consequences of this fact: the increase of the rate of the c-h process and a less effective feeding of the clouds. This second effect is the dominating one and causes the star formation rate to decrease. The decrease in the total mass of molecular clouds is shown in Fig. 5.1b.

After 10^9 years the decline in ψ becomes faster. During this phase the birth-rate shows a peculiar behaviour characterized by a sudden decrease followed by a roughly flat trend with a very small relative increase during rather a long time , then by an intense and sharp burst. The more prominent and articulate event, takes place at $t=7.06\times10^9$ years; the abrupt decrease of the birth-rate is of a factor of 25, the phase of slow growth lasts for 1.9×10^9 years and the sudden increase raises the rate by a factor of 500 in respect to the minimum. The duration of the burst is about 5×10^8 years. Another similar phenomenon occurs at $t=1.54\times10^{10}$ years.

Such behaviour is related to the presence of a small number of

SNRs: their scanty sweeping hardly affects the ambient gas which is on the contrary enriched by the mass lost by the low mass stars: the density n_a slowly grows and consequently the rate of star formation is quickly depressed (cfr. formula (4.17)), a further drop of ψ is due to the ensuing decrease of M_s. At the same time the number of molecular clouds is raised because they are consumed more slowly by star formation (now, after the SF fall, this is <10 times the previous one) than they are formed. This fact cause the slow change of ψ which, obviously, increases. The subsequent fast growth starts when the small increase of M_s is able to invert the tendency upwards of n_a that, with the higher value of M_{c_2}, permits larger efficiency of c-h process and then higher values of M_s. The large number of stars thus formed gives rise to a large ionizing radiation field which operates a drastic reduction of the number of clouds and consequently the birth-rate is again reduced.

Besides these events the birth-rate keeps on decreasing. After $6x10^9$ years the system is drawn toward a slow exhaustion: the cloud mass is reduced by three orders of magnitude, the total mass of massive stars is small (<100M$_\odot$); the ambient gas is very rarefied, its temperature is very high and his feeding by the last generations is insufficient to produce an inversion in n_a.

Table III shows some important quantities for the model at different stages.

This picture emphasizes the importance of ICM component and in particular of its feeding mechanisms on the system evolution.

Table III.

Model A1: fundamental quantities at different stages.

t (yr)	5×10^8	1×10^9	6×10^9	2×10^9	2×10^{10}
n_a (cm^{-3})	4.5×10^{-2}	1.9×10^{-2}	4.5×10^{-3}	7.9×10^{-4}	1.8×10^{-4}
T_a (K)	3.8×10^4	6.3×10^4	1.3×10^5	2.3×10^5	2.9×10^5
M_{c_2} ($M_\odot$)	1.6×10^7	5.1×10^6	7.4×10^5	7.3×10^4	1.1×10^4
M_s ($M_\odot$)	9.4×10^3	3.4×10^3	860	96	12

Table IV.

Models A1 and A2 at corresponding evolutionary stages.

Model	A1	A2
t (yr)	1.80×10^9	1.10×10^9
M_a ($M_\odot$)	1.0×10^4	1.40×10^4
n_a (cm^{-3})	9.4×10^{-3}	9.4×10^{-3}
M_{c_2} ($M_\odot$)	9.28×10^6	8.88×10^6
M_s ($M_\odot$)	3.40×10^3	1.66×10^3

The influence of the initial conditions and the other parameters

We consider now how a change in the initial conditions $n_a(0)$ and $M_{C_2}(0)$ and the values of the parameters η', R_{C_2}, and σ affects the evolution of the system.

<u>Change of the efficiency of star formation</u>.

The effect of this parameter can be analysed by comparing the model A1 with the model A2. This latter model, whose evolution is shown in Fig. 5.2, has been computed with a value of η' 5 times larger than that of A1 (Table II shows the values of the parameters of this model).

From the comparison of these two and other models (the range of η' which has been explored is from 2.5×10^{-5} to 5×10^{-3}) <u>the general conclusion is that the change in the efficiency does not alter the overall evolutionary behaviour but affects the lifetime of the system and the total mass of stars</u>: high efficiencies reduce the timescale and increase M_s.

In the Table IV the situation of model A1 at $t = 1.8 \times 10^9$ years is compared with the corrisponding stage of model A2 which shows the same values of M_a, n_a, M_{C_2}: this is reached at an age which is about the half of that of A1; the mass of M_s in A2 is also halved.

<u>Change in the initial conditions</u>: A) <u>the density of the ambient medium</u>.

Let us compare model A2 with model A3, which is shown in Fig. 5.3 and differs from the former because its initial value of the ambient density n_a is ten times larger (cfr. Table II).

In model A3, the c-h process cannot prevail until the ambient density is decreased by the sweeping of SNRs below a defined value $(n_a)_{cr}$, as before remarked (eq. 5.1); this is attained at $t=10^8$ years. In the model A2, owing to the rarefaction of the ambient medium the star formation process becomes very efficient after a very small interval from the beginning ($\simeq 10^6$ yr.) through the prevalence of the c-h process.

Comparison with model A1 brings one to the conclusion that the length of this first phase depends also on η' but when the ambient medium is initially rarefied ($n_a(0)<(n_a)_{cr}\simeq 0.1$ cm^{-3}) even in the case of low efficiencies, this first phase may become quite negligible; otherwise high efficiencies rise M_s and the sweeping of SNRs contributing to reduce n_a below $(n_a)_{cr}$ more rapidly .

B) <u>the total mass of the molecular clouds</u>.

Let us compare the following models, which differ only by the initial value of the total mass of molecular clouds: model A1 with $M_{c_2}(0)=8\times10^7$ M☉, model A4 with $M_{c_2}=8\times10^8$ M☉ and model A5 with $M_2(0)=8\times10^6$ M☉. Their evolution at some relevant stages is shown in Table V. It has already been shown that in model A1, after a small initial time interval, the ambient density tends to decrease since the sweeping by the SNRs is more important than the cloud photoionization. On the contrary in model A4, whose original cloud total mass is ten times larger, the density, after a rapid initial growth (due to the prevalence of the photoioinization over the sweeping) remains in a stationary state which clearly results from the balance of the feeding processes (cloud photoionization and, to a less extent, mass restitution from

Table V.

Evolution of models with different values of δ.

Model		A1	A4	A5
$M_{c_2}(0)$	$(M_\odot)$	8×10^7	8×10^8	8×10^6
$t=5\times10^8$ yr				
n_a	(cm^{-3})	4.5×10^{-2}	1.5	2.2×10^{-3}
T_a	(K)	3.8×10^4	1.2×10^4	2.1×10^5
M_{c_2}	$(M_\odot)$	1.6×10^7	7.2×10^8	2.7×10^5
M_s	$(M_\odot)$	9.4×10^3	310	452
$t=1\times10^9$ yr				
n_a	(cm^{-3})	1.9×10^{-2}	1.6	7.5×10^{-4}
T_a	(K)	6.3×10^4	1.2×10^4	2.3×10^5
M_{c_2}	$(M_\odot)$	5.1×10^6	7.2×10^8	6.8×10^4
M_s	$(M_\odot)$	3.4×10^3	300	97
$t=2\times10^9$ yr				
n_a	(cm^{-3})	4.5×10^{-3}	1.6	6.0×10^{-4}
T_a	(K)	1.3×10^5	1.2×10^4	2.3×10^5
M_{c_2}	$(M_\odot)$	7.4×10^5	7.2×10^8	5.1×10^4
M_s	$(M_\odot)$	860	290	72
$t=6\times10^9$ yr				
n_a	(cm^{-3})	7.9×10^{-4}	1.9	2.6×10^{-4}
T_a	(K)	2.3×10^5	1.2×10^4	2.7×10^5
M_{c_2}	$(M_\odot)$	7.4×10^4	7.2×10^8	1.7×10^4
M_s	$(M_\odot)$	96	260	22
$t=2\times10^{10}$ yr				
n_a	(cm^{-3})	1.8×10^{-4}	2.7	1.4×10^{-4}
T_a	(K)	2.9×10^5	1.2×10^4	2.9×10^5
M_{c_2}	$(M_\odot)$	1.0×10^4	7.2×10^8	2.9×10^3
M_s	$(M_\odot)$	12	220	10

stars and cloud evaporation) and the consumption process (sweeping by SNRs). The constant value of n_a is about two orders of magnitude larger than its initial value. The high ambient density restrains the c-h process keeping the rate of star formation, active only through the c-c process, at values much lower than the maximum value of the previous model: in this way the time required for the exhaustion of the system is considerably lengthened ($t>2x10^{10}$ years).

In model A5, with a smaller initial mass of clouds the c-h process becomes dominant as in the standard model, then SFR quickly decreases due to the more rapid exhaustion of the ICM. In particular this model in the last phase exhibits not star formation bursts (see next Sect.).

The analysis of these and other models allows the definition of a critical value, δ_{cr}, of the initial mass per unit volume $\delta = M_{c_2}(0)/ V$: δ_{cr}=0.1 M⊙ pc^{-3}, according to which the models can be grouped into two categories:

1) <u>models with $\delta<\delta_{cr}$</u> evolve qualitatively as model A1 and have a relatively short phase of very active star formation; depending on the values of η' and δ, their lifetime lasts for $10^8 \div 10^9$ years; $(n_a)_{cr}$ is a weakly function of δ again.

2) <u>models with $\delta>\delta_{cr}$</u> protract the active phase for times considerably longer and with a much smaller star formation rate. After $2x10^{10}$ years their ISM still consists of: a) clouds, whose total mass retains close to the original value; b) a warm, widely diffused, ambient gas with density of about 1 cm^{-3} and temperature of about $\approx 10^4$ K; c) a hot and rarefied gas, whose filling factor is very small, which corresponds to the hot cavi-

ties of SNRs; there are in fact few massive stars whose mass density is about $2x10^{-7}$ M⊙/pc³ .

From Table V it turns out that for $\delta<\delta_{cr}$ the earlier the phase of exhaustion of the star formation process begins, the smaller the total cloud mass. If $\delta>\delta_{cr}$ however (model A4) over 20 billion years the system is still stationary with a SFR relatilely lower (<<10 times) than the maximum value of the corresponding model with $\delta<\delta_{cr}$. The behaviour of the cloud mass is also different: in A4 it remains constant while in the other models it decreases quickly.

<u>In model with $\delta<\delta_{cr}$ the ISM tends, after a time interval which is function of δ (and η'), to a rarefied and very hot state</u>, but <u>if $\delta>\delta_{cr}$ the ambient gas rapidly evolves to a state more dense ($n_a>100n_a(0)$) and warm while the cloud total mass remains pratically constant around its initial value</u>.

<u>Change of the cloud parameters</u>

If in the relations (4.13), (4.18) and (4.21) the dependence on clouds mass m_{c_2} and on the density ρ_{c_2} is explicitly put into evidence, one gets:

$$A\propto \rho_{c_2}^{-.5};\ B\propto \rho_{c_2}^{.5};\ C\propto m_{c_2}^{.33}\rho_{c_2}^{.17} \qquad (5.2)$$

keeping the mass costant a decrease of the density (an increase of the radius) favours the importance of the c-c process in respect to the other two. The effect of <u>changing the cloud density, by keeping their mass constant</u>, can be analysed by comparing the models A6 and A7, whose parameters are shown in the Table II and whose evolution is represented in Fig. 5.4 and in Fig.5.5 respectively.

It is clear that as lower is ρ_{c_2} more rapidly the c-h process prevails on c-c which, in the first phase, increases M_s and the SNR number. In fact the c-c higher efficiency contrasts the effect of $n_a(0)>(n_a)_{cr}$ and reduces the first phase length . The evolution of the two models is qualitatively similar.

At constant density, an increase of the mass (and therefore a decrease of the radius), according to the relations (5.2), alters only the rate of c-s process. Since this process is always negligible, it turns out that a change of the mass of each cloud, at constant density, does not modify the evolution of the system.

Change of the parameter σ

The parameter σ, which has been introduced to correlate the photoionization rate to the stellar mass M_s, is important in influencing the evolution of the system inasmuch as it is related to the feeding of the ambient gas. On the other hand its value is affected by considerable uncertainty mainly because it is determined by extrapolations of observational data. It is interesting therefore to investigate what are the consequences of such uncertainty of the results.

To this purpose the model A1 of Fig. 5.1 is compared with the model A8, represented in Fig. 5.6, for which the adopted value of σ is ten times smaller.

In general for values of $\sigma > 10^{-14}$ $(M_\odot \ yr)^{-1}$ the process of cloud ionization becomes more effective, thus increasing the ICM density or hindering its decrease performed by the sweeping of SNRs. The higher value of n_a implies that the c-h process is late in being dominant (this circumstance is evident in model

A1). When the value of σ is sufficiently high ($\sim 10^{-12}$ ($M_\odot$ yr)$^{-1}$) the c-h process can remain secondary during all the evolution.

In the models with low values of σ (e.g. model A8) the ambient medium is always rarefied and the star formation rate quickly reaches a high peak, higher than corresponding value in models with higher σ because the ambient medium, less dense, cannot constrain the ψ rise. Then ψ decreases since the ambient medium, poorly feeded, cannot, in its turn, feed the cloud component. Such models, during the exhaustion phase, also show a larger number of oscillations in the stellar birth-rate than those found in model A1, in fact, at the same time, the relative importance of feeding on sweeping mechanisms is larger than that in the standard model.

Models with intermediate values of σ (as A1) exhibit a less pronunced maximum and a much slower decline phase.

Considering the total range of variations of σ one can conclude that the general behaviour of the system, when a high value of σ is used, is similar to that found for the models with $\delta > \delta_{cr}$ or that δ_{cr} is function of σ. The understanding of this behaviour ensues from the balances of the ambient gas and molecular clouds; these are expressed, in an approximate way, by the equations:

$$dM_a/dt = \sigma\, M_{c_2}\, M_s - K(n_a,T_a)\, M_a\, M_s \tag{5.3}$$

$$dM_{c_2}/dt = -\sigma\, M_{c_2}\, M_s + K(n_a,T_a)\, M_a\, M_s - \psi$$

where the second term of the right-hand member of both equations represents (the most important factors being put into evidence) the chain of processes: sweeping by SNRs, formation of HI clouds, formation of H_2 clouds; ψ denotes the total SFR.

If the initial total mass of clouds is large, so that $\delta>\delta_{crit}$, or if $\delta<\delta_{crit}$ but $\sigma>10^{-13}$ according to the first of (5.3) the photoionization prevails and mass and density of the ambient gas increase thus reducing the rate of the c-h process, in such a way that the c-c is the dominant star formation process. The larger ICM mass reduces the relative importance of the photoionization (eq. (5.3)) and the system attains a stationary value of M_a and also of M_{c_2} since the cloud consumption, because of the star formation, is small. In this case the model quickly attains a costant SFR and a long lifetime ($>2x10^{10}$ yr). The critical value of δ is therefore a function of σ, in the sense that for a model with a value of σ 10 times larger, the critical value, δ_{cr}, is approximately 10 times smaller.

Models with spontaneous star formation

According to Larson (1981) and Turner (1984) the star formation can start in a cloud in a spontaneous way as the result of the decay of the turbulence. This process has also been included in some models with its rate defined according to:

$$\psi_4 = M_{c_2}/\tau_{sp} \qquad (5.4)$$

where τ_{sp} is a time-scale which characterizes the clouds lifetime against spontaneous star formation. τ_{sp} cannot be determined by the observed cloud lifetime which also accounts for induced star formation: it can only be said that $\tau_{sp}>\tau_{c_2}$ where $\tau_{c_2}=4x10^7$ years is the determined lifetime.

Models A9 and A10 with $\delta>\delta_{cr}$ have been computed with $\tau_{sp}=10^9$ and

$\tau_{sp}=10^8$ years respectively; initial conditions and parameter values are those of model A4. In model A9 the star formation rate shows a short burst, as in absence of spontaneous star formation, although stronger because initially M_s is higher since the spontaneous star formation is higher than c-c process. Subsequently ψ settles, but only for a period of about three billion years, in a constant value, nearly 20 times as large as the rate of model A4. This enhanced star formation, which is the consequence of the spontaneous process, leads to the exhaustion of the ambient gas and the SFR slwoly decreases (cfr. Fig. 5.7). At $t=7x10^9$ years, conditions of the model A9 strongly differ from those of model A4 at the same age: they are rather typical of the exhaustion phase of the models with $\delta<\delta_{cr}$, although the lifetime of the system is much larger because longer is the stationary state.

The model with $\tau_{sp}=10^8$ years behaves qualitatively in a similar way as model A9 (cfr. Fig. 5.7 and Fig.5.8): the period of the constant SFR is shorter ($3x10^8$ years): the value of ψ is larger.

Models with $\delta<\delta_{cr}$ are not affected by the spontaneous star formation when $\tau_{sp}=10^9$ years; if $\tau_{sp}=10^8$ years the only effect is the suppression of the SFR oscillations since these are consequent on the small number of massive stars which,in this case, cannot drop below a certain level owing to the spontaneous star formation.

These considerations apply only in case when massive stars are formed. However if the spontaneous star formation process is able to form only low mass stars (Turner, 1984; also Sect. 3) the evolution of the model would not sensibly change: only the time required for the exhaustion could be shortened.

The influence of the lifetime of HI clouds

In order to simulate the process of formation of molecular clouds by a mechanism different from collision and coalescence of HI clouds, in some models equation (4.1) has been used with τ_{c_1} not defined by (4.2) but with a constant value. A lifetime of 10^7 years, in agreement with the observations, has been adopted for model A11 (see Table II), its evolution is presented in Fig. 5.9. The delay between the feeding of the ambient medium and the formation of molecular clouds is now reduced and this produces an evident stationary state of the SFR. In general the length of this state (here is about 4×10^8 years) rises as τ_{c_1} is shortened. After this phase the stellar birth-rate decreases more steeply than in the standard model, in fact there have been more SNRs during this longer time interval and thus the ICM has been eaten more than in the model A1. Thus the SFR oscillations start before and are more frequent as in model A8 (where $\sigma = 1.5 \times 10^{-14}$ $(M_\odot \ yr)^{-1}_{\circ}$

Obviously the models with $\delta > \delta_{cr}$ are independent of this assumption.

Variation of the supernova rate

In all the previous models the type I supernovae have been neglected. Owing also to the uncertainty of the lower stellar mass which originates type II supernovae, a new model has been computed in which the supernova rate has been artificially increased by a factor 5. The evolution of this model, in Table II under the symbol A12, is equal to that of model A1 but with the suppression of the bursts due to the increased sweeping of the ICM.

Figure captions

Fig.5.1 - Model A1. a) upper curve: total star formation rate ψ ($M_\odot$/yr); lower curve: total mass of stars with $m \geq 10\ M_\odot$, M_s ($M_\odot$). b) upper curve: total mass of molecular clouds normalized to the initial value; lower curve: ambient density normalized to the initial value.

Fig. 5.2 - Model A2. For explanation of this diagram compare Fig. 5.1.

Fig. 5.3 - Model A3. For explanation of this diagram compare Fig.5.1.

Fig. 5.4 - Model A6. For explanation of this diagram compare Fig. 5.1

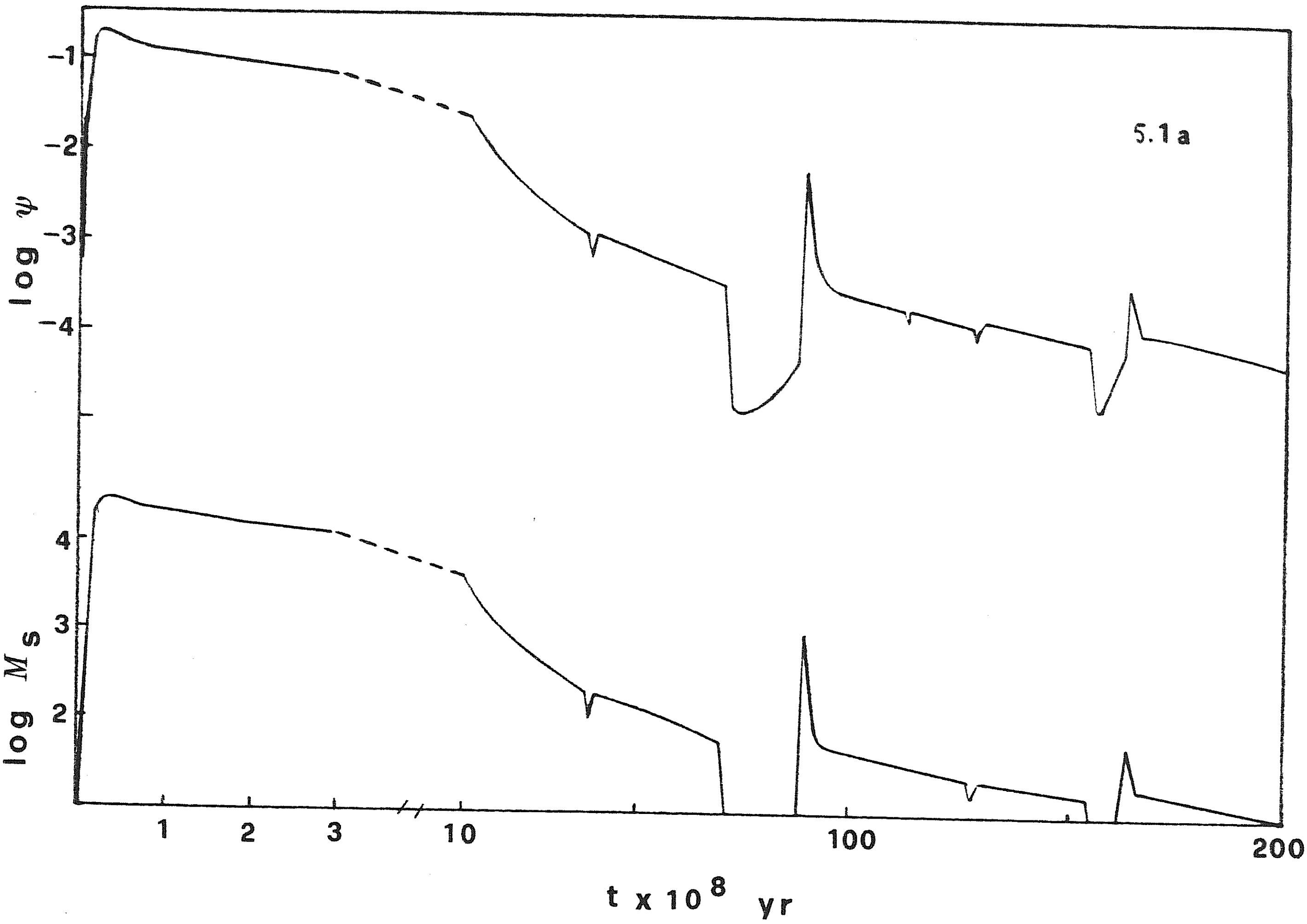
Fig. 5.5 - Model A7. For explanation of this diagram compare Fig.5.1.

Fig. 5.6 - Model A8. For explanation of this diagram compare Fig. 5.1.

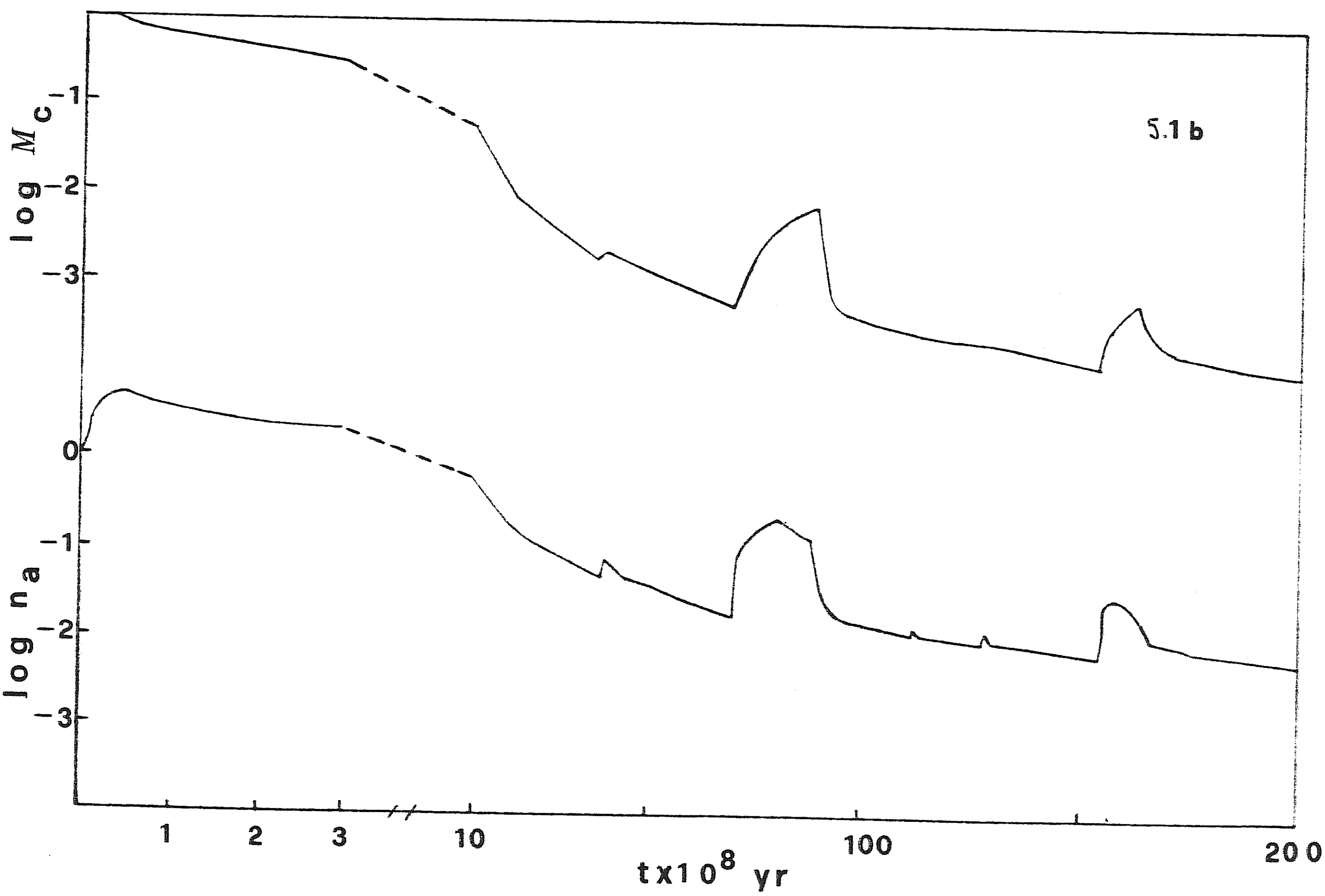
Fig. 5.7 - Model A9. For explanation of this diagram compare Fig. 5.1.

Fig. 5.8 - Model A10. For explanation of this diagram compare Fig. 5.1.

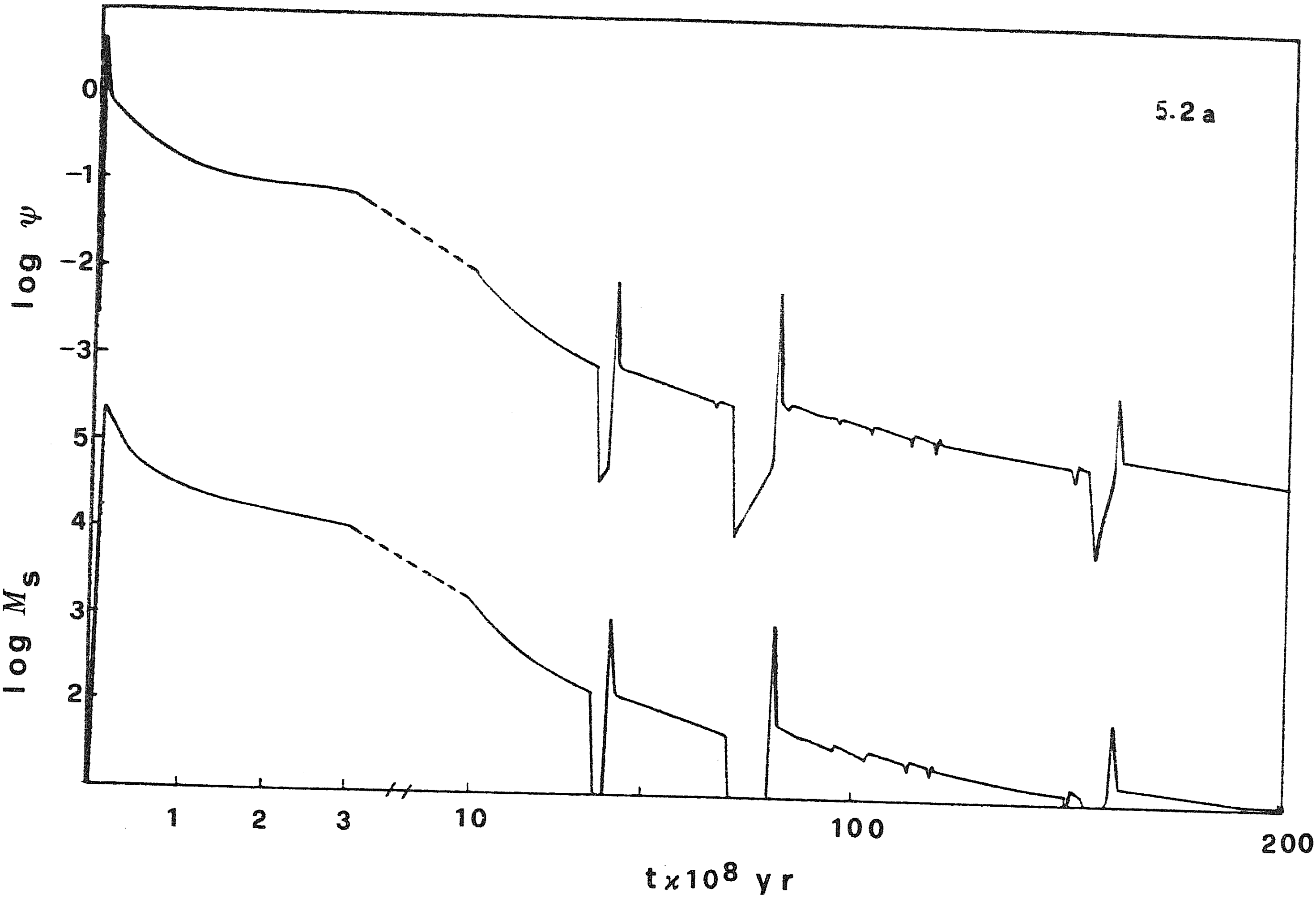
Fig. 5.9 - Model A11. For explanation of this diagram compare Fig. 5.1.



5.1a
log ψ
log M_s
-1
-2
-3
-4
4
3
2
1
2
3
10
100
200
t x 10⁸ yr



5.1b
log M_c
log n_a
-1
-2
-3
0
-1
-2
-3
1
2
3
10
100
200
tx10⁸ yr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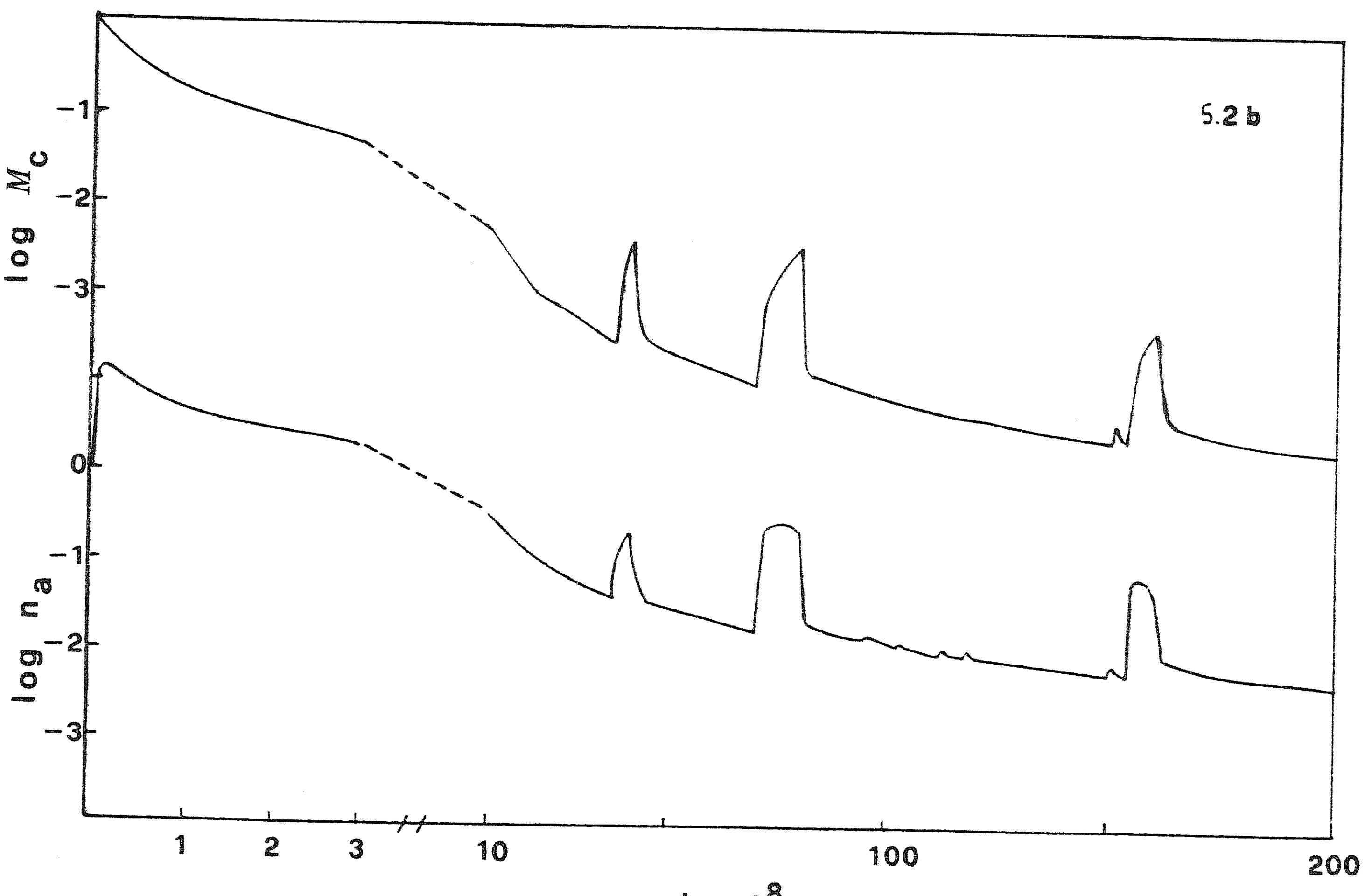
log ψ
0
-1
-2
-3
log M_s
5
4
3
2
1
2
3
10
100
200
t x 10^8 yr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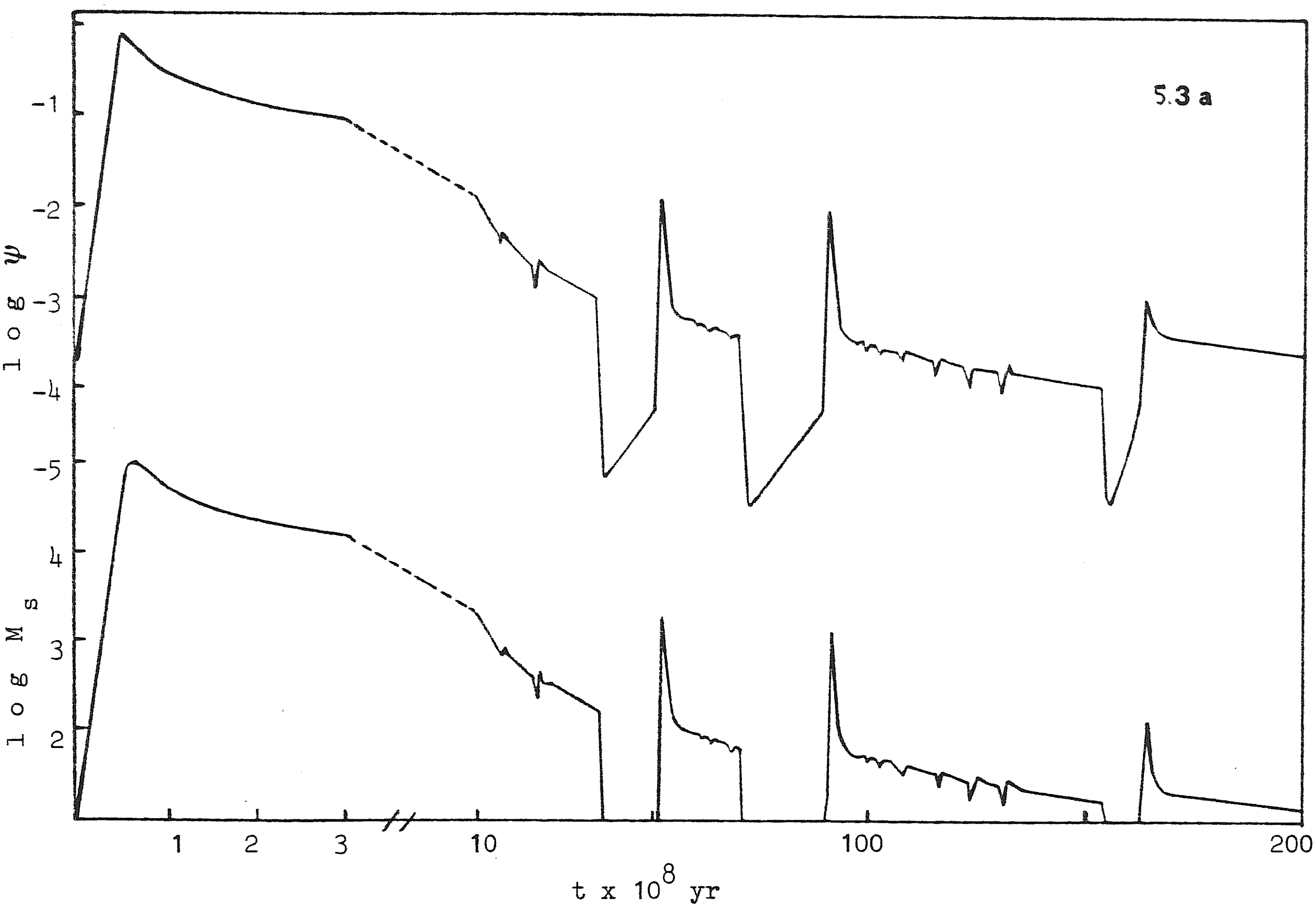
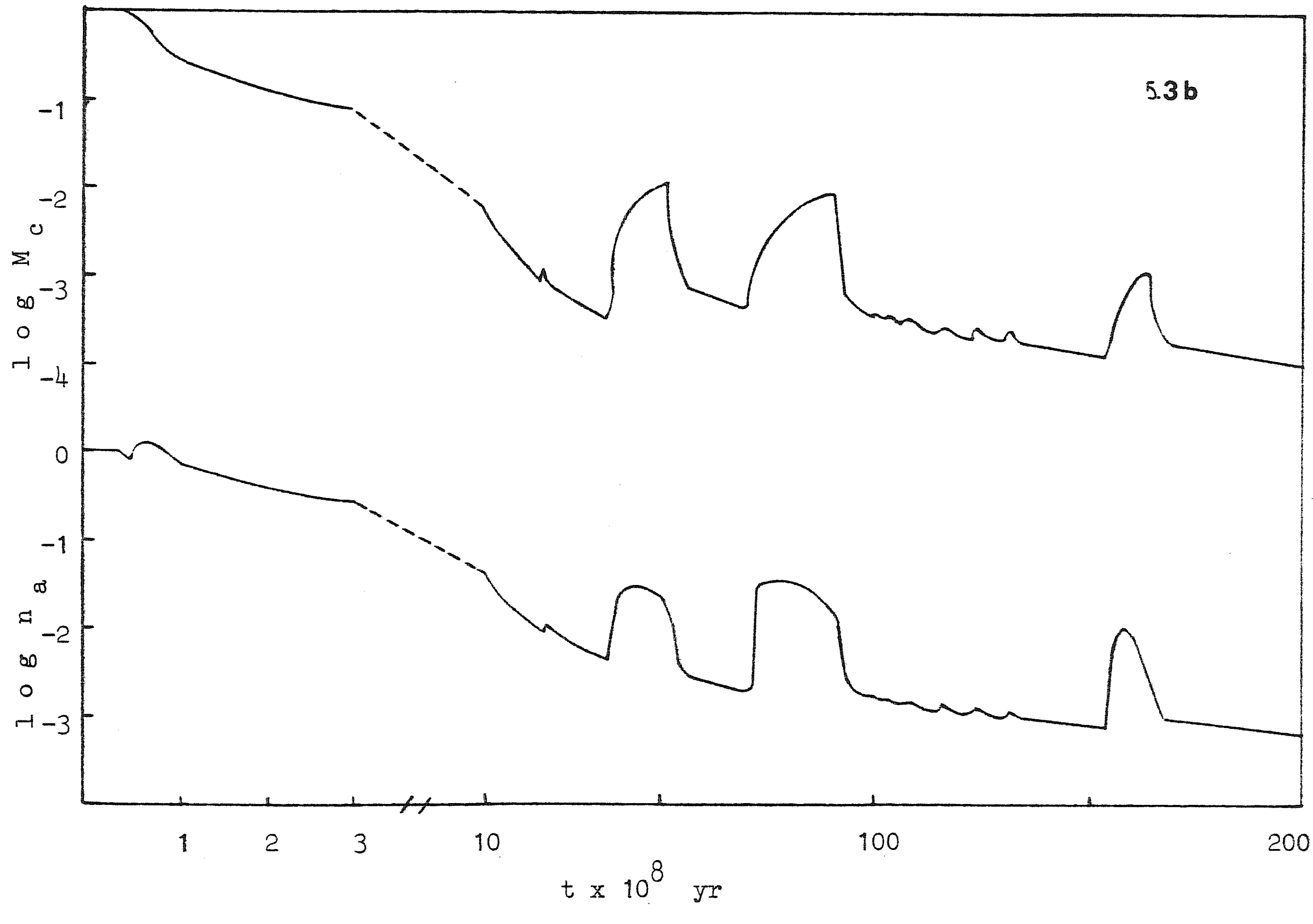
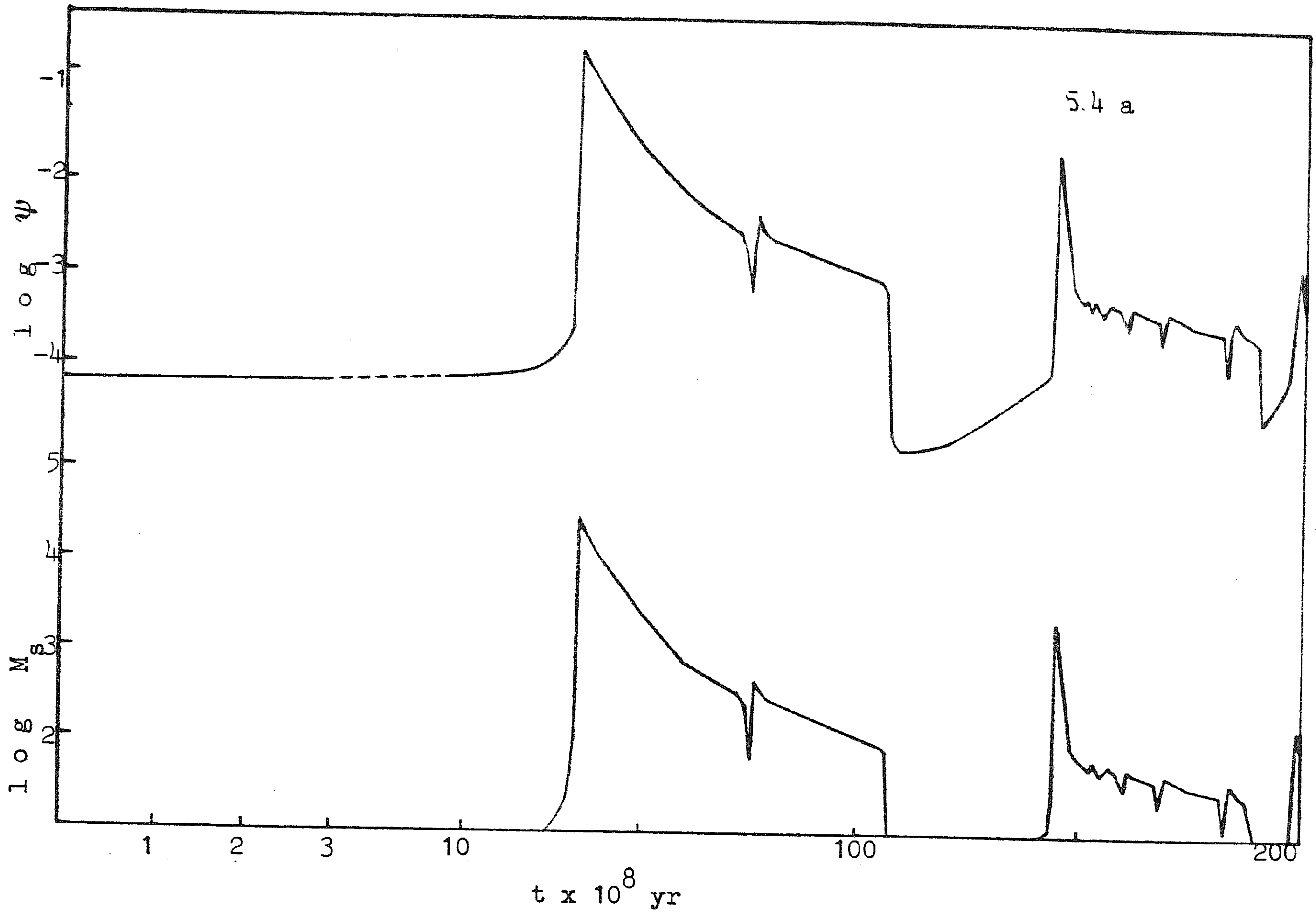
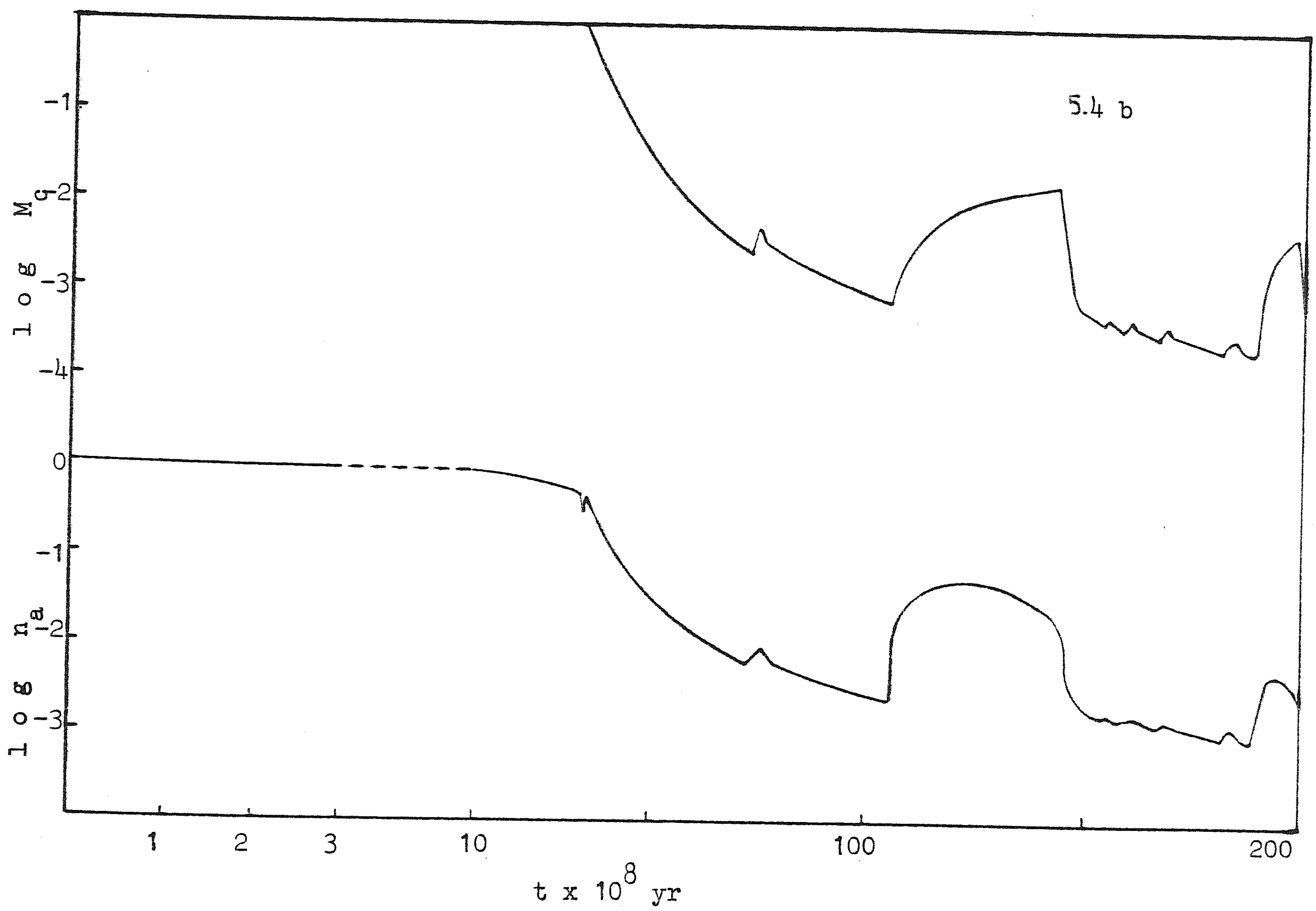
log M_c
-1
-2
-3
log n_a
0
-1
-2
-3
1
2
3
10
100
200
t x 10^8 yr


5.3 a
log ψ
-1
-2
-3
-4
-5
log M s
4
3
2
1
2
3
10
100
200
t x 10^8 yr


5.3 b
log M c
-1
-2
-3
-4
log n a
0
-1
-2
-3
1
2
3
10
100
200
t x 10^8 yr


5.4 a
log ψ
-1
-2
-3
-4
5
4
3
2
log M_s
1
2
3
10
100
200
t x 10^8 yr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log M_g
-1
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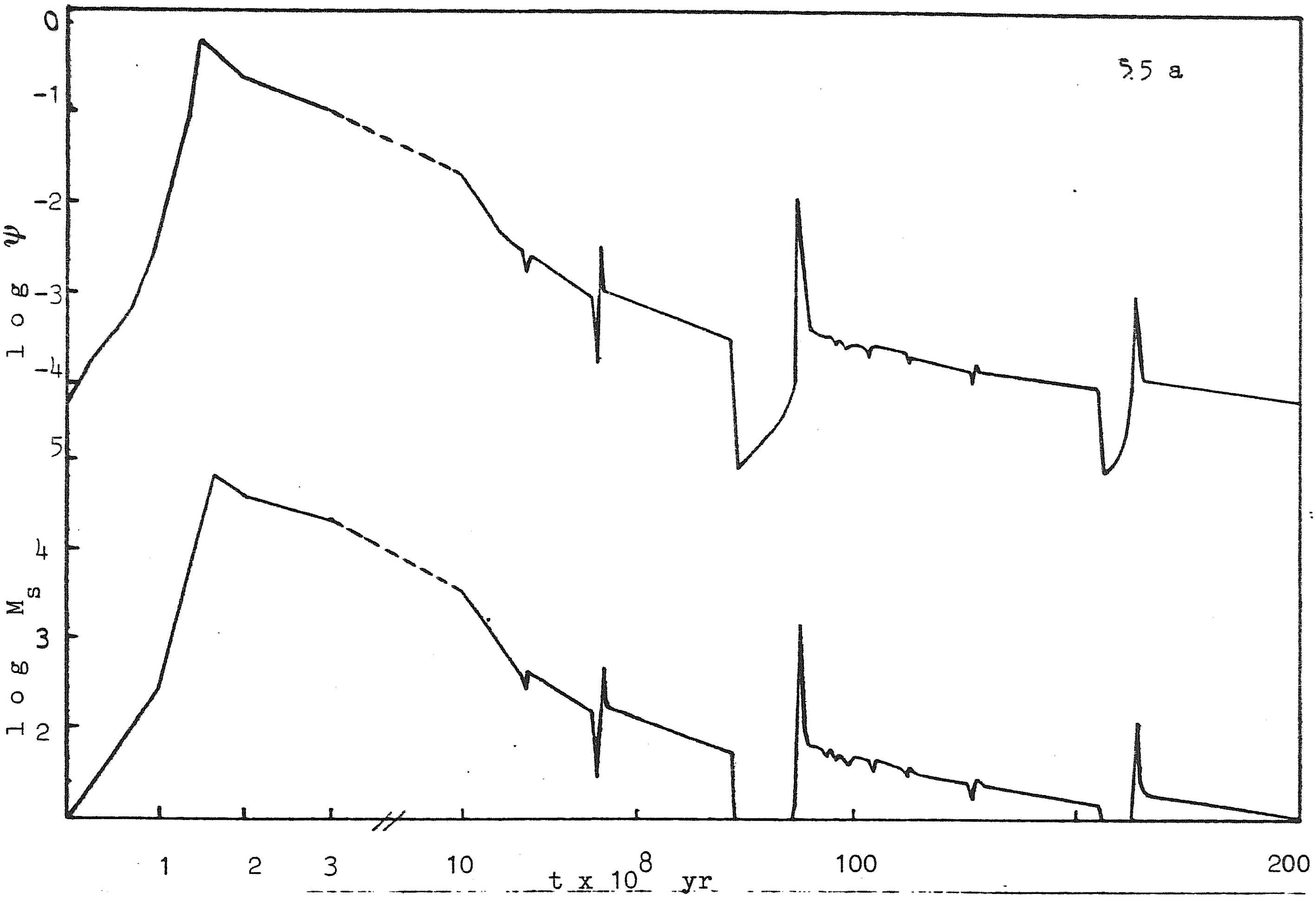
-3
-4
0
-1
-2
-3
log n_a
1
2
3
10
100
200
t x 10^8 yr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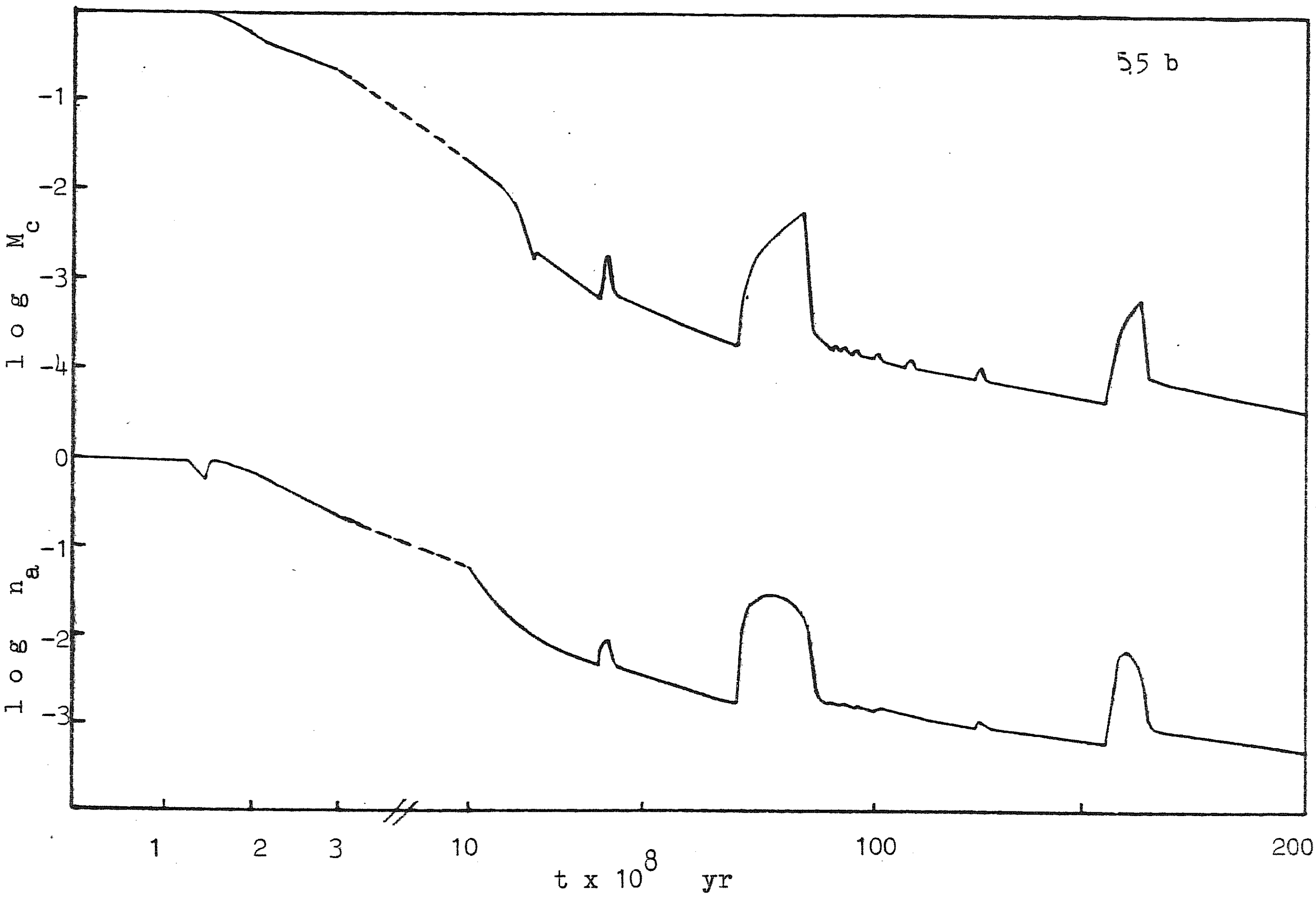
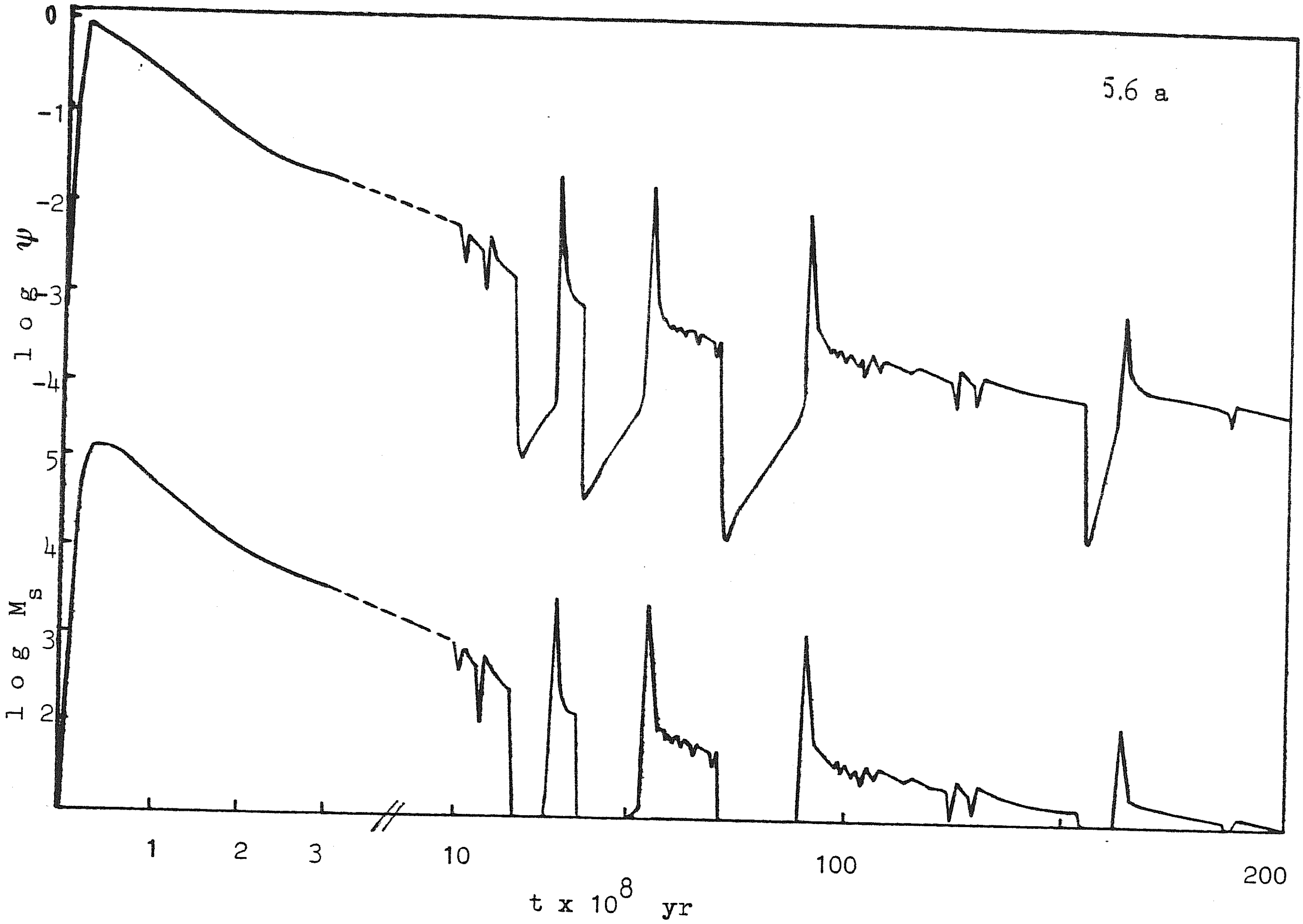
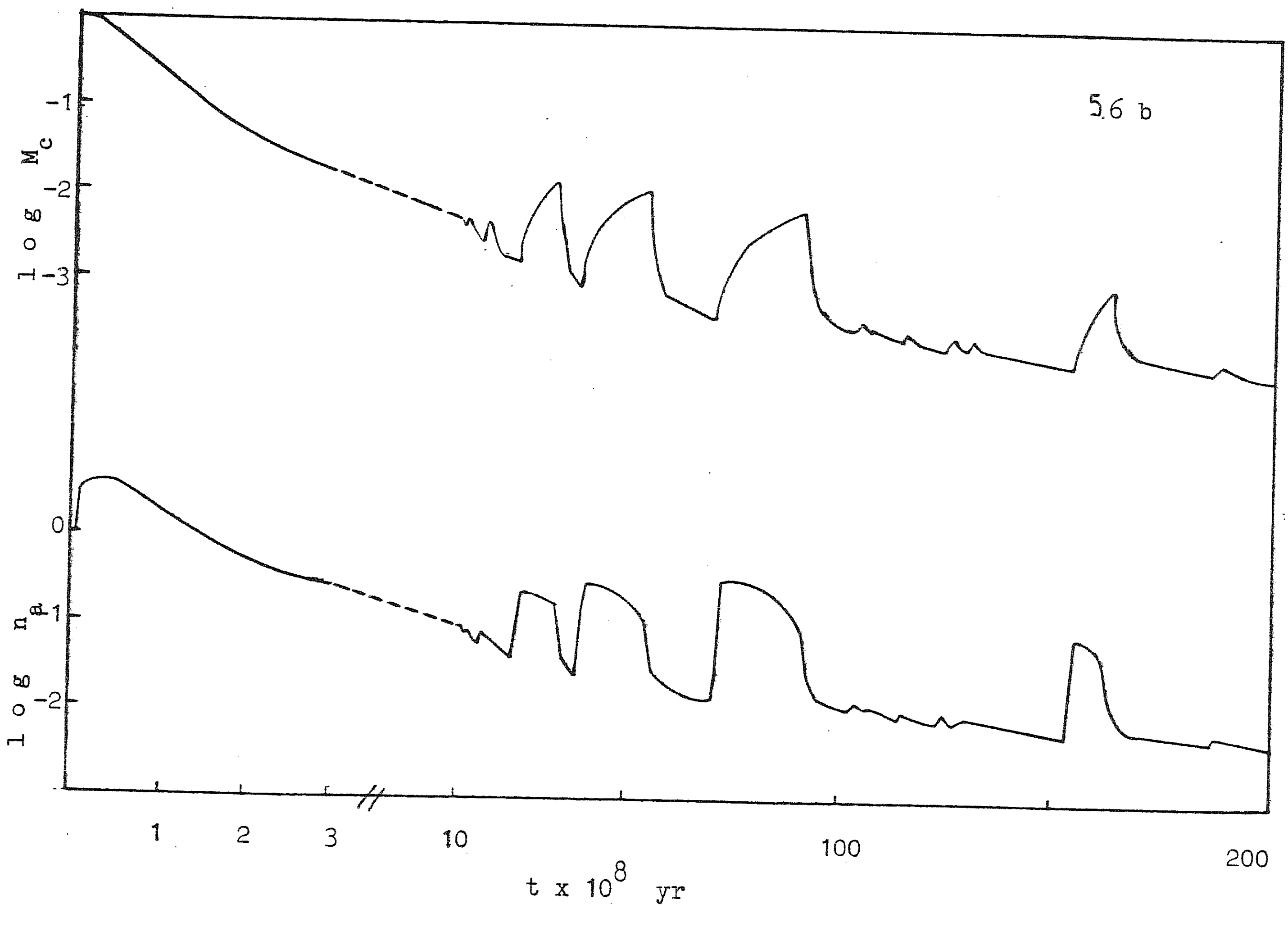
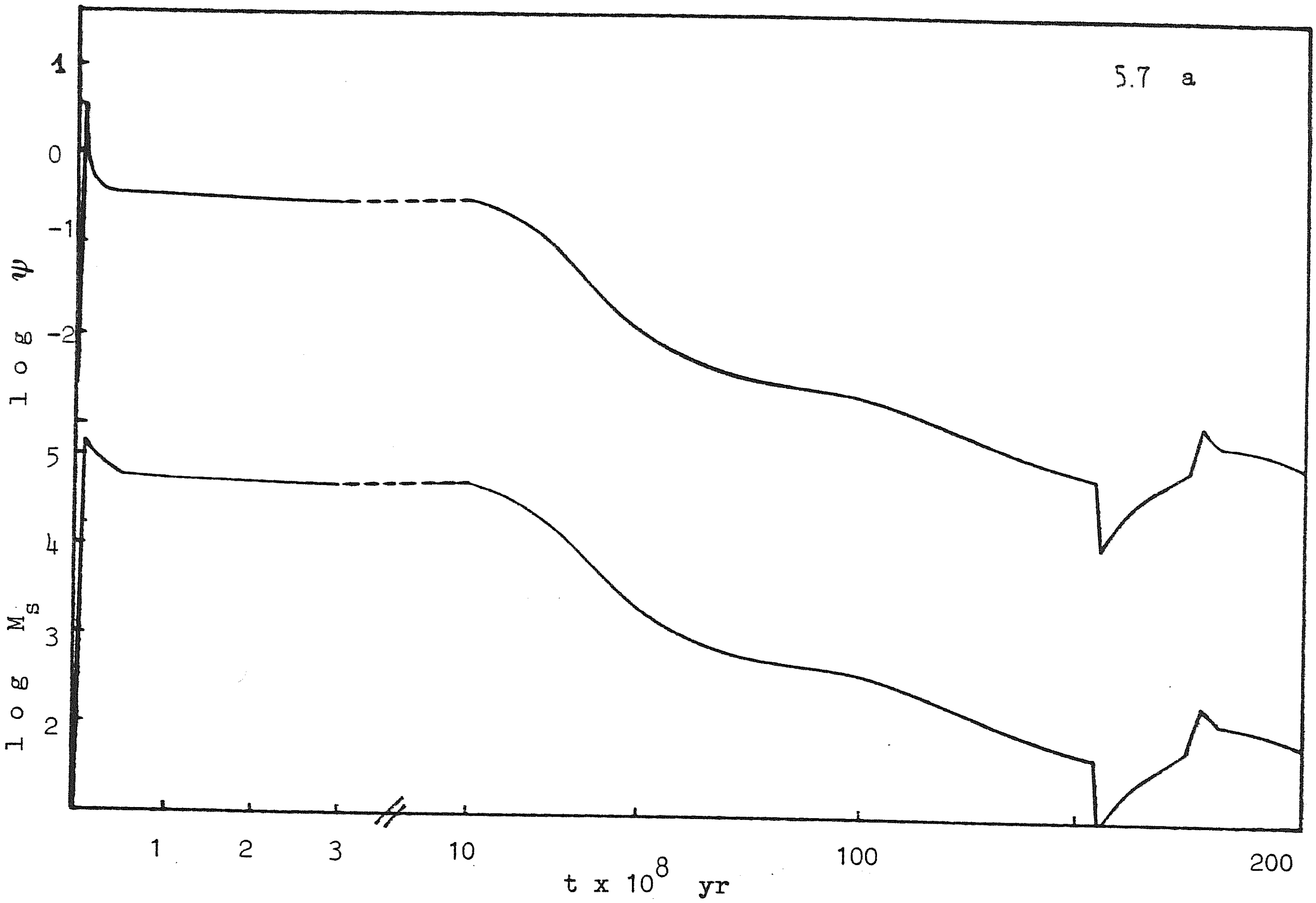
0
-1
-2
-3
-4
5
4
3
2
log ψ
log M_s
1
2
3
10
100
200
t x 10^8 yr

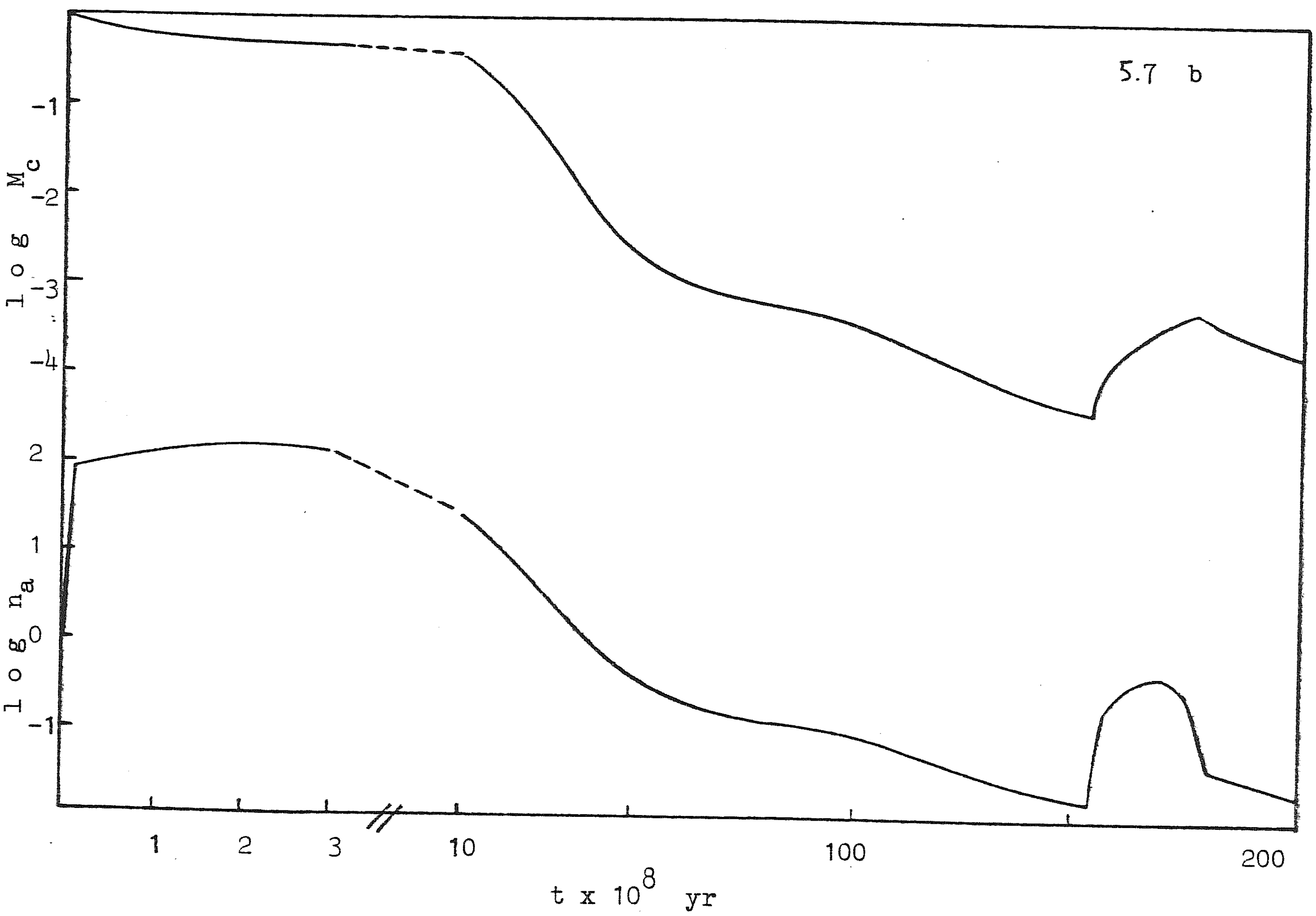

5.5 b
-1
-2
-3
-4
0
-1
-2
-3
log M_c
log n_a
1
2
3
10
100
200
t x 10^8 yr


5.6 a
log ψ
log M_s
0
-1
-2
-3
-4
5
4
3
2
1
2
3
10
100
200
t x 10^8 yr

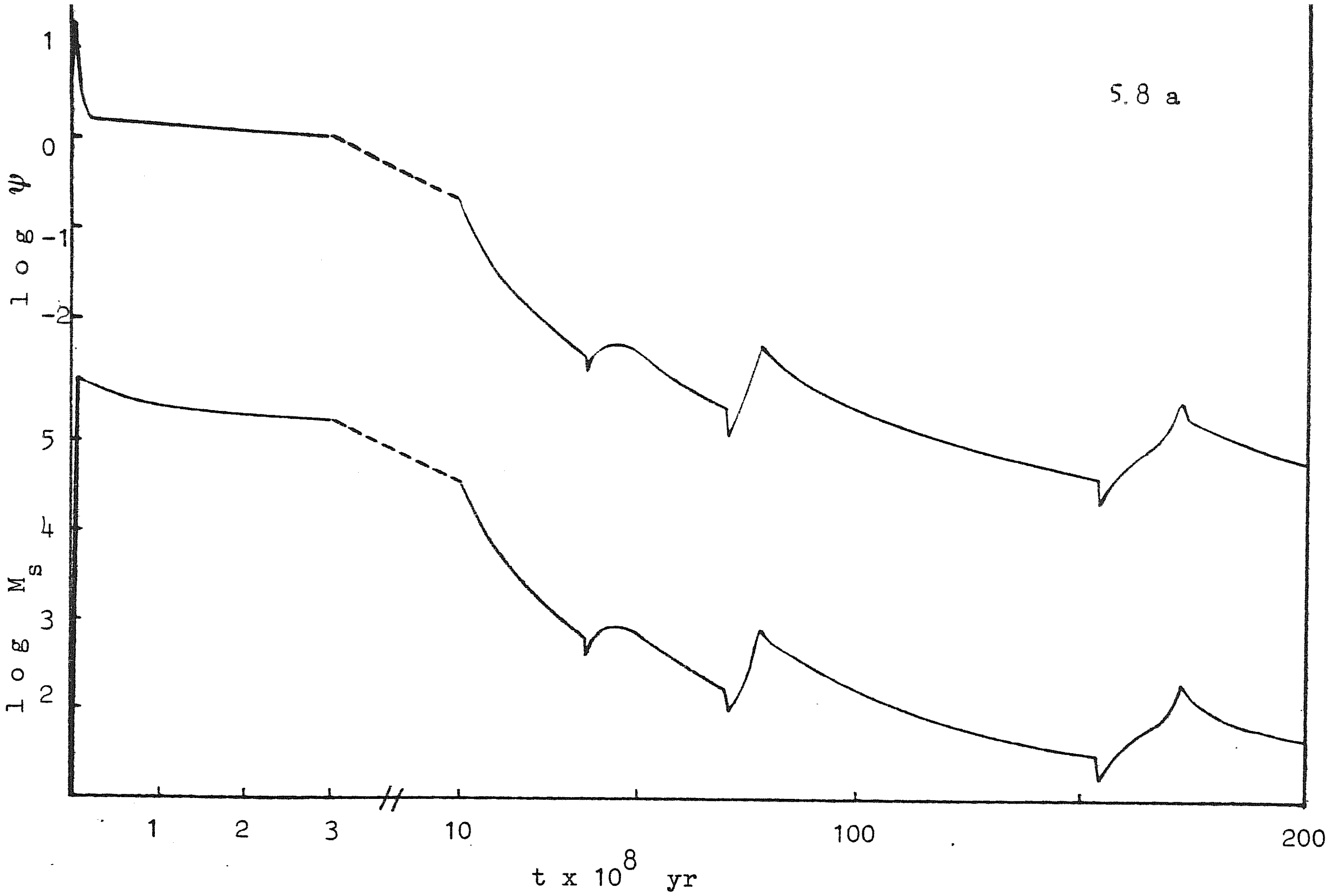

5.6 b
log M_c
log n_a
-1
-2
-3
0
-1
-2
1
2
3
10
100
200
t x 10^8 yr



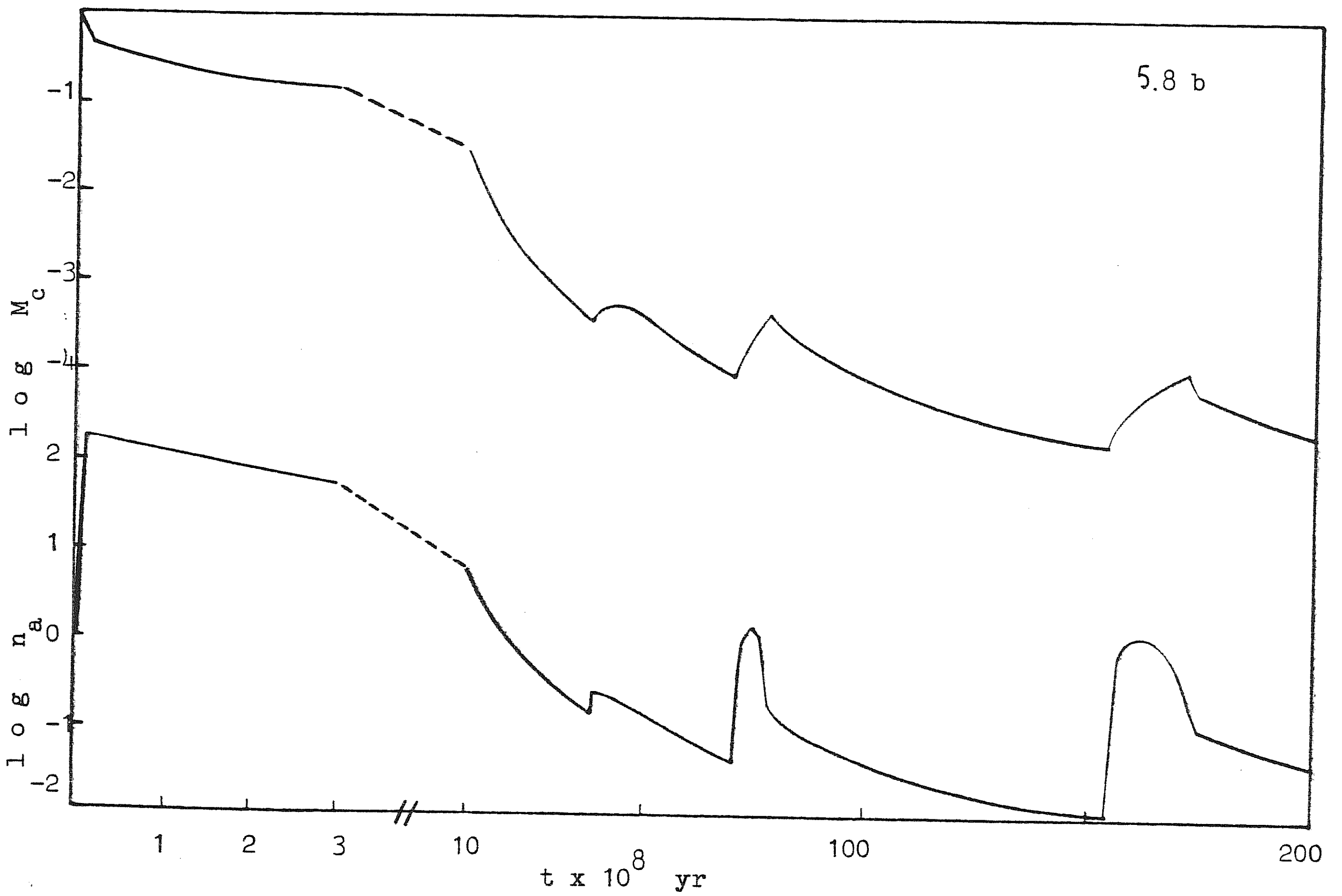
5.7 a
1
0
-1
-2
log ψ
5
4
3
2
log M_s
1
2
3
10
100
200
t x 10^8 yr



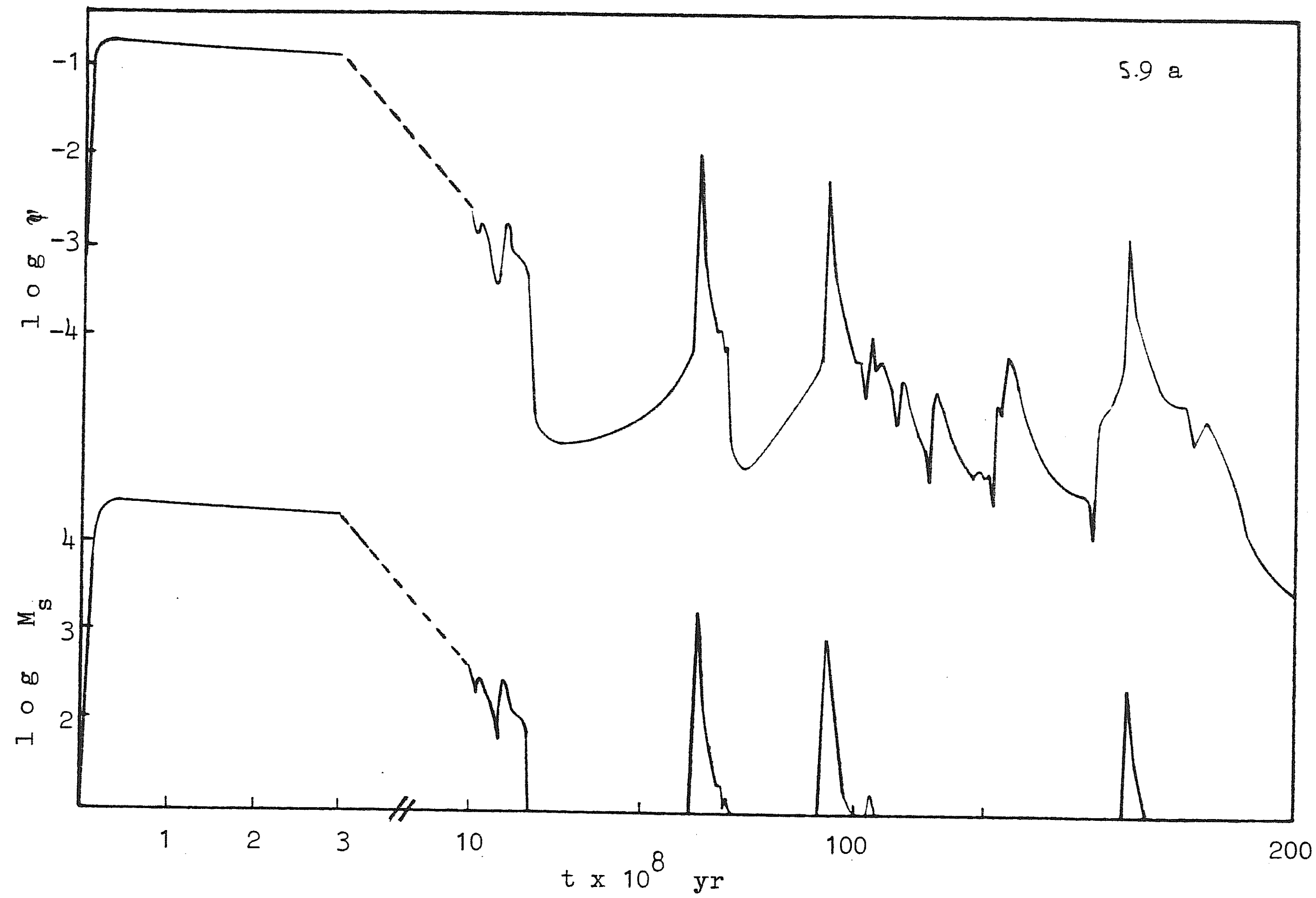
5.7 b
-1
-2
-3
-4
log M_c
2
1
0
-1
log n_a
1
2
3
10
100
200
t x 10^8 yr

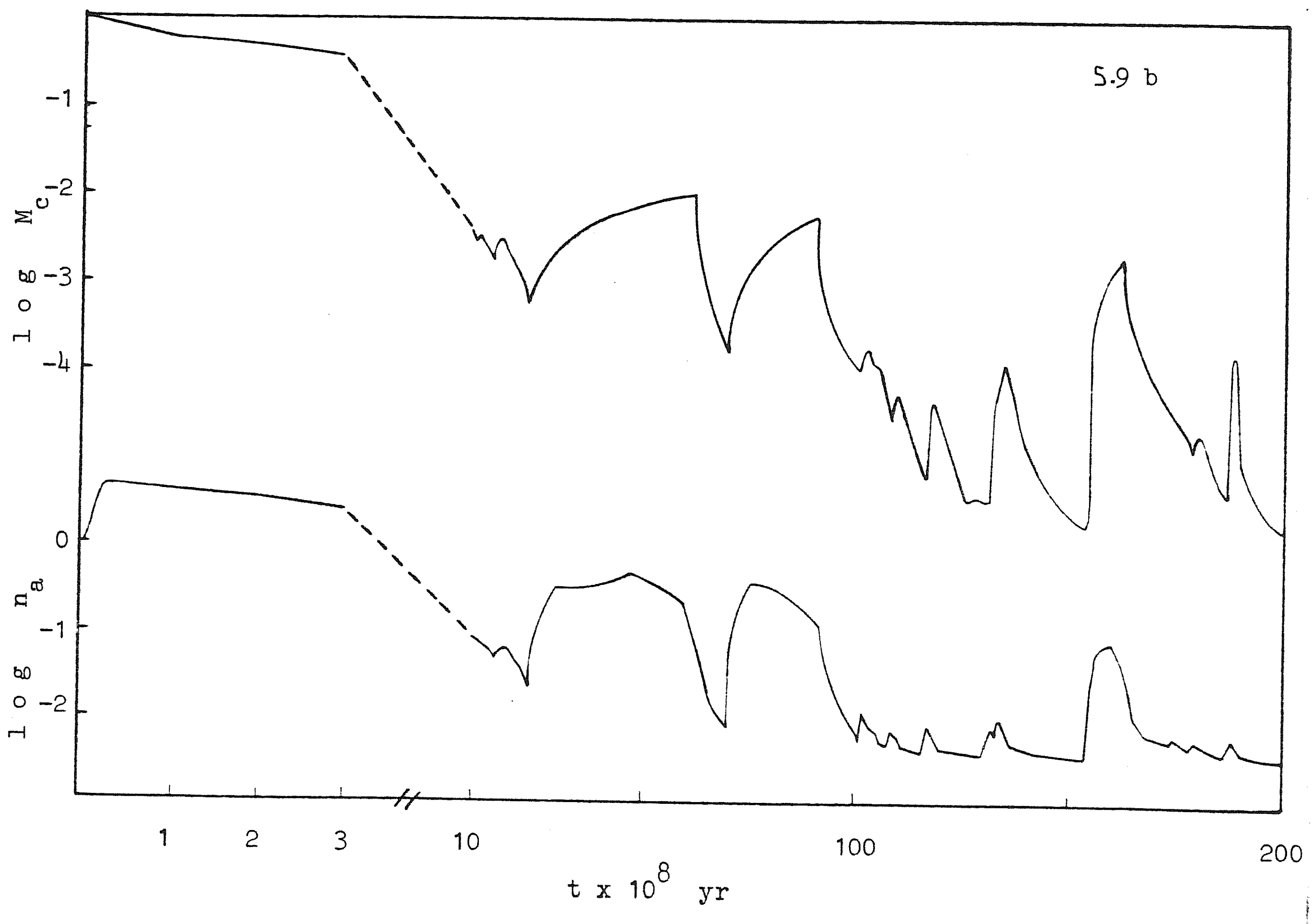


5.8 a
log ψ
1
0
-1
-2
log M_s
5
4
3
2
1
2
3
10
100
200
t x 10^8 yr



5.8 b
log M_c
-1
-2
-3
-4
log n_a
2
1
0
-1
-2
1
2
3
10
100
200
t x 10^8 yr


5.9 a
log ψ
-1
-2
-3
-4
log M_s
4
3
2
1
2
3
10
100
200
t x 10^8 yr


5.9 b
log M_c
-1
-2
-3
-4
log n_a
0
-1
-2
1
2
3
10
100
200
t x 10^8 yr

S E C T I O N 6.

CONCLUSIONS

Introduction

A model has been developed which describes the evolution of the ISM taking into account the interactions between all its components. The purpose is to look into the mechanisms of induced star formation and ascertain how and to what extent they are affected by the physical conditions of the ISM. Moreover the consideration is restricted only to SFR in molecular clouds of intermediate mass as a first step in the study, more complicated, of the giant molecular complexes.

The interactions between the ISM components, which we have considered, are numerous and the mathematical formulation of the problem leads to a system of non-linear equations with several loops. On this basis it is expected that the conditioning of the ISM on the star formation processes is heavy and in fact this has been confirmed by the analysis of all the computed models.

Summary

The following conclusions have been reached:

1) we have considered three mechanisms of induced star formation (Sect. 4) but only two are important, the c-c and the c-h processes,their relative weight depends on the original conditions of the ISM in the galactic volume such that only one of these characterizes the evolution of the system.

2) The total initial cloud mass per unit volume, δ, decides if the ICM feeding prevails over its consumption, as consequence δ settles the dominant SFR mechanism and then the system lifetime. If the initial total mass of clouds per unit volume is large, so

that $\delta>\delta_{crit}$, [according to the first of (5.3)] the feeding prevails and mass and density of the ambient gas increase thus reducing the rate of the c-h process, in such a way that the SFR is drived by the c-c process. The larger ICM mass reduces the relative importance of the feeeding mechanism and the system attains a stationary value of M_a and also of M_{c_2} thus the SFR is costant and the system lifetime is longer than $2x10^{10}$ yr.

One can assert that to a large initial number of clouds an always large number of clouds follows and consequently the SFR keeps at relatively low values.

If, on the contrary, the total mass of the clouds is originally small (as in models with $\delta<\delta_{crit}$), the ICM consumption prevails on the feeeding mechanisms so the c-h process becomes quickly dominant and raises the SFR at high values; the maximun of the SFR is more than 10 times larger that in the previous case, leading to the exhaustion of the system in $\approx 10^9$ yr.

3) The effect of the other initial condition, $n_a(0)$, is always limited to an initial phase since the ambient density can be quickly modified depending on δ which regulates also the value $(n_a)_{cr}$ such that if $n_a(0)<(n_a)_{cr}$ the c-h process from the very beginning is the only efficient star formation process.

4) The whole analysis has shown the importance of the interchange mechanisms between the several components which self-regulated the system evolution and in particular produce the apparently paradoxical result that a high original cloud number (pc^{-3}), instead of giving rise to an active star formation process, makes

it slower.

i) After, possibly, the first initial phase, the cloud mass M_{c_2} reaches a value almost constant (for $\Delta t>2x10^{10}$ yr if $\delta>\delta_{cr}$) or very slowly decreasing for a very short (if $\delta<\delta_{cr}$) but significative interval of the lifetime of the system (which represents the phase of very active SFR). This value for M_{c_2} is derived from the second of (5.3) by setting $dM_{c_2}/dt=0$:

$$M_{c_2} = K(n_a,T_a)\ M_a/(\ \sigma + B(n_a)) \cong K(n_a,T_a)\ M_a\ /\ \sigma \qquad (6.1)$$

and is therefore a function only of the conditions of the ambient gas and of σ. The value of the SFR is then related to the ambient conditions both directly (eq. 4.17) and indirectly since n_a controls also M_{c_2} by two processes which balance themselves: a) the cloud photoionization which acts as a (twice) negative feedback because increases the ambient density (and partially reduces the cloud mass) and then lessens the rate of star formation; b) the cloud formation which evidently is a (twice) positive feedback since feeds M_{c_2} (and reduces n_a).

It must be remarked that such phase of constant M_{c_2} or of slow decrease does not appear in the models with a low value of σ because the going up again of n_a is inable to produce the necessary fuel for M_{c_2}.

ii) In models with $\delta<\delta_{crit}$ during the exhaustion phase, when M_{c_2} decreases at a significant rate, the following relation has been found to hold:

$$\log\ (\psi/M_s) = \text{const.} = K \qquad (6.2)$$

where the value of K is constant not only for a given model during the whole final phase but it is approximately the same for all the computed models: it turns out K=-6.85 where the dispersion is 25%. From the comparison of this relation with th rate of the c-h process one gets:

$$M_{c_2} = \lambda(\eta') \; n_a^{4/3} \qquad (6.3)$$

with $\lambda(\eta')=10^K/B(\eta')$ where the dependence on η' has been brought into evidence (eq. 4.18). This relation is an indication that the selfregulating mechanisms act within the system.

These results emphasize the important role in the system evolution of the ICM (or n_a). The physical state of this component, which in its turn depends on δ, is reflected on the SFR and on the global behaviour of the system. This component acts as a go between stars and clouds and, as a result of δ value, permits to reach a partial ($\delta<\delta_{cr}$) or total ($\delta>\delta_{cr}$) steady state.

5) Moreover in the last phase of the models with $\delta<\delta_{cr}$ <u>mechanisms of feeding of the ICM can lead to star formation bursts</u>. In this work the system is isolated and this event is caused by mass loss from low mass stars. Otherwise we can aspect that mass interchanges, due to different large-scale mechanisms (Struck-Marcell and Scalo, 1986) or to contact interactions between elements of galactic volume (Seiden and Gerola,1986), significantly affect the SFR in them: these effects could transform a model with $\delta<\delta_{cr}$ in one with $\delta>\delta_{cr}$ and could represent a feeeding source in the last phases of the evolution if $\delta<\delta_{cr}$.

The burst possibility is an intrinsic property of non-linear systems as Shore (1981, 1983) analized and his general rules are also true in our model although the fundamental equations are quite different. The burst starts in the advanced phases only if the SFR is smaller than mass loss rate from low mass stars and if $M_{c_2}/V>10^{-4}$ M⊙/pc³ is remained (the model A5, for example, has never bursts).

The evolution of the UBV colours before, during and after the bursts has been computed according the procedure and the calibrations described in Barbaro and Olivi (1985). The length of the bursts and the changes of the integrated colours $(U-B)_0$ and $(B-V)_0$ by them produced, seem to be in agreement with the observed galaxies (Larson and Tinsley,1978): the maximum change of the colours due to the burst at 7x10⁹ yr for the standard model is $|(B-V)_0|=0.20$ and $|(U-B)_0|=0.35$.

6) The results are very weakly dependent by the several parameters of the model (Sect. 4 and 5) with the exception of σ (eq.4.9). In other words the evolution is qualitatively the same because only depends on the initial conditions,in particular on δ as above-mentioned. Only these conditions regulate the relative importance of feeding and consumptions mechanisms which, in their turn, lead to the prevalence of the c-c or the c-h process and therefore define the final configuration of the system. Different values of the other parameters modify only the length of the several phases ($\delta<\delta_{cr}$), not the same evolution. However δ_{cr}, which represents the discriminant value between two categories of models with different histories of star formation, is related to the σ value.

7) The inclusion of a process of spontaneous star formation affects significantly the evolution of models with $\delta>\delta_{crit}$ pro-

vided that the time scale of this process is shorter than or equal to 10^9 years; it is does not, on the contrary, have any effecton the models with $\delta<\delta_{crit}$ except for the exculsion of bursts if $\tau_{sp}=10^8$ yr. However these conclusions are correct only if massive stars can form also in the spontaneous process (see Sect. 3).

8) It is possible, within the limits of the model, attempt a galactic application of the results as suggested by two aspects.

i) During the phases in which the cloud mass is constant or slowly decreasing ($\delta<\delta_{cr}$) no correlation is found between the star formatiom rate and the total mass of molecular clouds nor the total mass of clouds. But, in the advanced phases, the following mean relations have been found:

$$\psi = R\ (M_{C_2})^n \qquad \psi = R'(M_{C_1} + M_{C_2})^{n'} \tag{6.4}$$

The value of n does not change significantly from model to model: the average value is n=.97 with a 15% dispersion; on the contrary R varies within two orders of magnitude, thus reflecting the dependence on the other factors. In the second relation (6.4) the average value of n' is 2.13 with a dispersion larger than 50% . Relations (6.4) are very similar to those found by Rana and Wilkinson (1986b) by analysing the data of the disk of our galaxy, according to them n=1.12 while for the total mass of gas the range of variation of n' is between 1.7 and 3.1 .

We would point out that if c-c collisions and gravitational instabilities (from spontaneous SF) were the general mechanisms of star formation in the disk of our galaxy, the expected dependence on n would be different (2 and 1.5 respectively). The result which we have obtained seems suggest that the star formation mechanisms now prevailing are self-regulated (by action of the ICM) and self-propagating (by the presence of M_s) mechanisms. From comparison of the first of (6.4) with equation (4.17) one gets that, for each model with $\delta<\delta_{crit}$ in the exhaustion phase, $M_s \approx (n_a)^{4/3}$: the mass of the stars depends on the ambient conditions, a result which has also been found for M_{C_2} (eq. 6.3).

ii) The result that, depending on the initial number of clouds per unit volume, both the prevailing mechanism of star formation and the order of magnitude of the SFR are different, suggests some considerations about the galactic evolution.

If elliptical galaxies originate from a non-dissipative collapse of stars alone, as suggested by Gott (1973, 1975) since the gas has already been consumed in forming stars, the c-h mechamism should have been the dominant process: such systems should have originated in regions where the initial number of clouds per unit volume was small. In regions however where this number is large, in such a way that it results $\delta>\delta_{crit}$, the gas should not be quickly converted into stars and should collapse, thus forming a disk (dissipative collapse: Gott and Thuan, 1976).

Within the scenario suggested by Larson (1974a, 1974b, 1975, 1976) for the collapse of a gaseous system, when the infall rate is larger than the rate of consumption of clouds by the photoionization, the c-h mechanism could be inhibited. The larger number of clouds per unit volume can transform a model where initially $\delta<\delta_{cr}$ in one with $\delta>\delta_{cr}$ leading to the formation of a spiral system instead of an elliptical one. The angular momentum, the other initial conditions being the same, could be the discriminating factor between the two modes of formation.

GMC model: preliminary results

An overall picture of the process of star formation must evidently take into account the molecular complexes, which, in our galaxy, include a large fraction of the molecular gas (Scoville et al, 1984; see also Sect. 2) and for which we can expect, a priori, a different behaviour of the processes of induced star formation since HII regions and SNRs expand, partly or entirely, in a denser medium.

In order to ascertain whether and to what extent the general results concerning the star formation analysed in this work, are changed by the different conditions of the ambient gas I'm preparing an other model.

Preliminary results of this model of a molecular complex with an overall mass of 10^6 M$_\odot$, a volume of 10^7 pc^3 and a number of clumps ranging from 10 to 100 (in such a way that it results $\delta<\delta_{crit}$) confirm the prevalence of the c-h process during almost the whole lifetime of the complex.

In evaluating the efficiency of star formation processes the results derived by Elmegreen (1983) for the molecular complexes have been considered.

The condition for the disgregation, as derived from Hills (1980) assumes that the complex breaks up when more than 50% of the gas has been swept away by HII regions and SNRs. From the computed models the lifetime of the complex ranges from 10^7 to 6×10^7 years: the cause for the disgregation is the action of the HII regions alone or combined with that of SNRs.

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