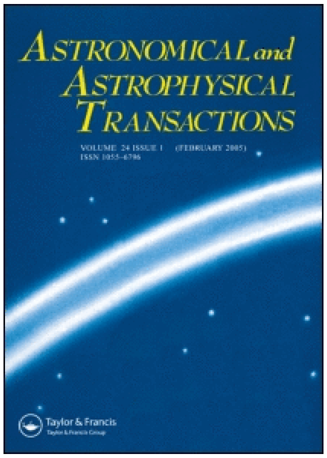

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LARGE-SCALE COHERENT BEHAVIOUR OF STAR FORMING SYSTEMS WITH FEEDBACKS

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The star formation (SF) influenced by penetrating heating radiation is discussed. This radiation can affect SF in two ways: on the one hand, it can stimulate the SF process by provoking implosion of interstellar clouds which are optically thick to the heating radiation; on the other hand, the heating radiation exposing optically thin clouds neutralizes SF. So, heating radiation can be a link connecting a monitoring feedback loop of SF: birth of stars → generation of heating radiation → photoimplosion (or photoevaporation) of interstellar clouds → triggering (or inhibition) of star formation. The characteristic size of the region covered by the action of this feedback is of the order of the extinction length of the heating radiation. For UV photons with $\lambda > 912$ Å passing in diffuse interstellar gas, it is about 0.3–1 kpc depending on gas density. This length is argued to be the length of synchronous behaviour of SF. The relation of this mechanism with the observed large-scale star-bursts is discussed.

1 INTRODUCTION

Recent progress in theoretical and observational studies of galaxies and stellar clusters has led to a very fruitful conception of self-regulated star-gaseous systems, which can be considered as a good "caricature" of real stellar systems. The key idea of this conception is based on the effect of stimulation or inhibition of SF by the stars of the previous generation. It is well known that energy injected by stars into the interstellar medium (ISM) by radiation, stellar winds and supernova explosions influences the physical state of the ISM and causes amplification or depression of SF depending on new, perturbed state of clouds population. The ways in which this influence can be carried out are supposed presently to be as follows:

- amplification of gravitational fragmentation of interstellar gas by shock waves generated by ionizing fronts (Oort, 1954; Elmegreen and Lada, 1977), by stellar winds (Blitz, 1980), and by supernova explosions (Öpik, 1953; Herbst and Assousa, 1977);
- squeezing and subsequent triggering of gravitational contraction of interstellar clouds by Ly-c radiation near OB-stars (Dibai and Kaplan, 1964; LaRosa, 1983; Elmegreen, 1992);

- heating of interstellar clouds by penetrating heating radiation from newly born massive stars (Suchkov and Shchekinov, 1979; Parravano, 1988; Parravano and Thronson, 1990).

These mechanisms are obviously the elements of a system of feedbacks governing galactic structure and evolution. From this point of view, the first two groups of these mechanisms (triggering of cloud's contraction by shock waves and ionizing radiation) can be described as short-range positive feedbacks: newly born stars stimulate the formation of the stars of the next generation in the system with the characteristic scale of action equal to the size of quite evolved SN remnants, stellar wind bubbles, or HII-regions, ~ 10–30 pc (Lada *et al.*, 1978). At smaller scales these "contact" influences destroy cloud's phase due to thermal- (Cowie and McKee, 1977) or photo- (Elmegreen, 1976) evaporation and play the role of an inhibitor of SF, and so, can be defined as a short-range negative feedback. A distinctive feature of short-range feedbacks in star-gaseous systems is a wave-like character of the SF: the perturbation creating the SF is transmitted by steps expanding from an initial seat of star birth with the characteristic velocity $U_{\rm SF} \sim 3$–5 km/s (Elmegreen and Lada, 1977; Lada *et al.*, 1980). This is analogous to the expansion of flame in a combustible medium. There are no doubts that the wave-like self-exciting SF really exists: the signs of such SF are seen in Cep OB3, Ori OB1 (Blaauw, 1964, Lada *et al.*, 1978), and Shapley III constellation in the LMC (Dopita *et al.*, 1985).

At the same time, it is obvious that the large-scale dynamics of galaxies cannot be governed by such local mechanisms. Suchkov and Shchekinov (1979) have suggested a new large-scale negative feedback regulating the global behaviour of SF in our Galaxy. They proposed this idea to explain the discontinuity in the halo and disk stellar populations. The main idea of this mechanism is that the enhancement of the flux of penetrating heating radiation generated by active stars prevents the condensation of interstellar gas into the cloud component, and after the heating radiation flux reaches some critical value the cloud population is destroyed completely. So, stellar activity plays here the role of an inhibitor of the SF. Parravano (1988) reformulated this mechanism and developed an elegant scenario of galactic evolution in which the SF is assumed to be self-regulated in such a way as to maintain the interstellar gas at the marginal thermally stable state. Parravano and Thronson (1990) argue that this mechanism can be dominating for a wide range of physical conditions in star-forming systems: from SOs to infrared luminous galaxies.

The concept of self-regulated star-forming systems would be complete if it included a large-scale positive feedback. This type of regulating feedback is expected to provide a burst-like behaviour of SF over the whole system initiated by a localized SF embryo. Such a possibility has been demonstrated actually by the first pioneering investigations of self-regulated star-forming systems with positive feedbacks in the framework of the one-zone model which really implies a global synchronization (Shore, 1981; Bodifee and de Loore, 1985). The next logical step to the "one-zone" approach was proposed recently by Ferrini *et al.* (1992): in this model two global components, the halo and the disk, are assumed to be connected by a large-scale regulating mechanism. The competition between global ("one-zone") positive and negative feedbacks has been shown to cause, in general case, non-stationary SF behaviour (oscillating or burst-like), providing a natural physical explanation of periodic or sporadic starburst activity of galaxies (Searle *et al.*, 1973; Huchra, 1977).

At present, the observed starburst activity of galaxies is believed to be determined, for the most part, by mergings or tidal interactions. At the same time, some starburst galaxies are evidently isolated: apparently most of IRAS galaxies in the lower luminosity range L(FIR)$< 10^{11} \sim L_\odot$ are not interacting (Scalo, 1987; Leech *et al.*, 1989); there is a quite numerous sample of "normal" (no-IRAS) isolated galaxies (predominantly, Sc and SBc) with extremely active, ~~bursting star~~ formation (Richter and Rosa, 1988). Richter and Rosa argue that "..presumably all galaxies are forming their massive stars in bursts.." with the duration of the burst phase about 10^7 yr and the recurrence timescale of about 10^9 yr, and that the burst phases have a galaxy-wide character. Thus, these burst events cannot be caused by the small-scale positive feedback pointed above. So, the starburst phenomenon looks as if a galaxy was a one-zone self-regulating region as described by Shore (1981) and Bodifee and de Loore (1985). Note that the recurrency of SF allows to assume that there is a large-scale negative feedback depressing the SF synchronously. (Although it is quite possible that the gaps of SF can be connected with the depletion of cold gas able to convert into star – Suchkov and Shchekinov, 1979). This prompts to seek for internal mechanisms of the large-scale feedback that could synchronize the SF process over the whole galaxy.

The aim of this paper is to describe one of the possible mechanisms of the large-scale synchronization (Cammerer and Shchekinov, 1991, 1993). The outline of the paper is as follows. In Section 2 we describe qualitatively the basic "microscopic" mechanism of the large-scale positive feedback – the implosion of interstellar clouds by heating radiation. In Section 3 we present a simple analytical description of such a feedback and its characteristic features. Section 4 is concluding one.

2 PHOTO-IMPLOSION OF INTERSTELLAR CLOUDS

The compression of interstellar clouds immersed in an HII region by exposing to Lyman continuum radiation was described quantitatively by Dibai and Kaplan (1964). LaRosa (1983) studied this problem in thin-layer approximation including the self-gravity of the radiatively compressed clouds. Recently, the dynamics of clouds subject to ionizing radiation was investigated in detail by Bertoldi (1989) and Bertoldi and McKee (1990). The main conclusion for the theory of SF is that the ionizing radiation absorbed by the external layer of a cloud stimulates cloud compression, and, under certain conditions, the formation of a self-gravitating condensation.

Kovalenko and Shchekinov (1992) have shown that the diffuse heating (not ionizing) UV radiation $\lambda > 912$ Å induces a similar dynamics of interstellar clouds outside HII regions. Thus, UV radiation released by massive stars can stimulate the SF process on the scales corresponding to the extinction length of UV photons in the interstellar medium, $L_{\rm UV} \sim 0.5 \times 10^{21}$ cm$^{-2}/n$ (n is the local number density of the ISM), for the warm intercloud gas with $n \sim 0.2$ cm^{-3}, this is $L_{\rm UV} \sim 1$ kpc.

Let us consider qualitatively the main characteristic features of the implosion of interstellar clouds by heating UV radiation. A detailed description is given by Kovalenko and Shchekinov, 1992, 1994). For a cloud with the radius R_c and number density n_c, the exposing UV photons are absorbed in the layer of the thickness $L_{\rm ab} \sim (n_c\sigma_{\rm UV})^{-1}$. Here $\sigma_{\rm UV}$ is the extinction cross-section at $\lambda \sim 1000$ Å, and we take $\sigma_{\rm UV} = 2.5 \times 10^{-21}$ cm^2 and assume $R_c > L_{\rm ab}$. It is well known that absorbed UV photons induce photoemission of electrons from dust grains (Jura, 1976). The ejected electrons lose their energy in elastic collisions with thermal electrons and heat the surrounding gas at the rate

$$H_{\rm UV} \sim 10^{-25}\, n_c\, U_8 \ {\rm erg\ cm^{-3}s^{-1}}, \tag{1}$$

where $U_8 = U/(10^{-8}$ photons cm^{-2}s^{-1}Hz^{-1}) is the interstellar radiation field at wavelength $\lambda \sim 1000$ Å.

Let us assume that at initial time the cloud and intercloud gas are in pressure equilibrium and in a thermally balanced state supported by UV heating. Thus, the stationary state is described by the following equations:

$$P_c = P_{ic}, \tag{2}$$

$$H_c = \Lambda_c(T_c)\, n_c^2, \tag{3}$$

$$H_{ic} = \Lambda_{ic}(T_{ic})\, n_{ic}^2, \tag{4}$$

where subscripts "c" and "ic" belong to the cloud and the intercloud gas, respectively; p, n, T are the pressure, number density and temperature; $\Lambda(T)$ is the cooling function, $H_c = H_0 + H_{\rm UV}(\tau)$ is the heating rate for the cloud gas with H_0 determined by the heating radiation for which the cloud is transparent (X-ray photons with energy $E_{\rm X} > 1$ keV, Cammerer and Shchekinov, 1993, hereafter CS), τ is the optical depth of the clouds external absorbing layer to the heating UV photons (generally speaking, this dependence provides inhomogeneity of density and temperature inside the cloud); $H_{ic} = H_0 + H_{\rm UV}$.

The dynamical response of the cloud and the intercloud gas to variations of the exposing UV flux is determined mainly by the temperature dependence of the cooling functions $\Lambda_c(T)$ and $\Lambda_{ic}(T)$. At lower temperatures corresponding to the cloud gas, Λ is a power-law function, $\Lambda_c(T) = A_cT^\nu$, with $\nu \approx 1.3$ in the interval $T = 10$–300 K (see Kaplan and Pikelner, 1979). This provides a power-law response of the cloud temperature to a suddenly increased UV flux:

$$T_c(\tau < 1) \sim \left(\frac{h_0 + B\,U}{A_c n_c}\right)^{1/\nu}, \tag{5}$$

where the cloud temperature in the external layer with optical depth less unity is on the left-hand side and the heating rate is taken in the following form: $H_0 = (h_0 + BU)n_c$. The cooling function of thermally stable intercloud gas at $T \sim 10^4$ K is determined mainly by neutral hydrogen cooling due to the excitation of the 2p-state and it can be estimated as $\Lambda_{ic}(T) \sim A_{ic} \exp(-\Delta E/T)$ with $T \ll \Delta E (\sim 1\ \text{Ry})$. As a result, the variation of intercloud temperature caused by the variation of the heating UV flux is logarithmic:

$$T_{ic} \sim \Delta E/\ \ln\ (A_{ic}\, n_{ic}/(h_0 + B\, U))\,. \tag{6}$$

Let at the moment $t = 0$ the exposing heating UV flux to increase suddenly at the characteristic time smaller enough than the characteristic time of the dynamical response of the cloud: $t_d = R_c/v_{sc} = 10^6\ (R_c/1\ \text{pc})\ (v_{sc}/1\ \text{km/s})^{-1}$ yr, where v_{sc} is the sound speed in the cloud. In such a case, increasing of U leads to increasing of pressure in the external layer of $\tau \sim 1$ in accordance with eq. (5):

$$P_c(\tau \sim 1) \propto (h_0 + B\, U)^{1/\nu}. \tag{7}$$

At the same time, the external (intercloud) pressure increases rather slow:

$$P_{ic} \propto \ln (h_0 + B\, U). \tag{8}$$

This means that at such circumstances initial stages of the cloud dynamic evolution are determined by the pressure excess in the boundary layer of the cloud. Obviously, this pressure excess generates simultaneously an inflow directed to the cloud's centre and an outflow directed outside the cloud.

This qualitative consideration of the cloud implosion by the heating radiation is confirmed by numerical calculations conducted by Kovalenko and Shchekinov (1992). The pressure excess induced by absorbed UV radiation in an external optically thick layer of the cloud generates compressing motions which lead to a considerable contraction of gas in central parts due to the cumulative factor r^{-2}. The degree of compression depends on the density of released UV energy in the absorbing layer: so, the more opaque is the cloud and the higher is the exposing UV flux, the larger is the central density at maximal compression. For example, the UV flux three times larger than the observable value $U_8 = 1$ creates the maximal central density about 5 times the initial unperturbed value for a cloud with the total optical depth $\tau = 1.67$, and about 20 times for $\tau = 3.34$. This central peak disappears after the relaxation time has elapsed, equal to the characteristic hydrodynamic time of the cloud in the models without gravity. The situation changes qualitatively when self-gravity is included into consideration. In this case an additional increase of density near the cloud centre accompanied with excess cooling can diminish the stability of the cloud against gravitational forces. So, even if the cloud is undercritical at initial unperturbed state (i.e., its mass is smaller than the Jeans critical mass), after the heating radiation initiates cumulative motion, it can acquire a nuclear overcritical region in the sense that specific gravitational energy (per unit mass) in the central region exceeds the specific positive (thermal and kinetic) energy. In this case the radiatively driven contraction can be changed into an irreversible gravitational contraction of a central part of the cloud. Numerical calculations including self-gravity demonstrate that the formation of a gravitationally bound nucleus is possible for photoimploded clouds with the mass of 0.4–0.5 Jeans masses corresponding to the initial unperturbed state (Kovalenko and Shchekinov, 1994). This means that increasing of diffuse UV flux decreases the lower limit of the mass of gravitationally unstable clouds, and can stimulate star formation.

Two important circumstances should be stressed here. Firstly it is obvious that in non-spherical symmetry the cumulative geometrical factor is not so sharp as r^{-2}, and maximal compression is weaker than in the previous case of exact spherical symmetry. Anisotropy of exposing radiation seems to have similar consequences for the contraction. However, the general tendency of UV heating radiation to stimulate hydrodynamical motions directed towards the cloud nucleus is undoubtedly preserved. Secondly, it is well known (see, e.g., Myers, 1978) that turbulent motion in giant molecular clouds, which are believed to be the sites of SF, are subsonic. So, one would think that the effective pressure exceeds sufficiently the external gas pressure, and the pressure excess caused by the UV absorbed seems to be negligible. However, it should be taken into account that a major fraction of giant molecular clouds consist of compact dense clumps whose random motions represent the turbulent velocity field in velocity maps (Bertoldi and McKee, 1992). In this picture the clumps are confined by the pressure of the surrounding material, and in such a case they can be influenced considerably by the radiatively driven implosion.

Nevertheless, it is quite enough for our purposes to assume that the excess of the exposing UV flux leads to increasing of pressure at the cloud boundary in accordance with relation (7) neglecting the cumulative amplification during compression.

3 A SIMPLE MODEL OF COHERENT SF

3.1 Equation for Star Formation

The basic suggestion of our model is that the rate of formation of massive stars is proportional to the total mass of clouds in the system with the mass of an individual cloud larger than the critical mass (CS)

$$\dot{S}_{\mathrm{F}}(r, t) = A\, t_c^{-1} \int\limits_{M_{\mathrm{cr}}}^{\infty} \Phi(M)\, dM, \tag{9}$$

where

$$M_{\mathrm{cr}} = M_{\mathrm{cr}}(r, t) = \frac{k\, T_c^2}{\mu^2\, G^{3/2}}\, P_e^{1/2}$$

is the critical isothermal spherical mass confined by external pressure P_e, undergoing self-gravitating collapse (it is easy to show that M_{cr} is optically thick to UV photons if the internal pressure of the cloud exceeds 300 K cm^{-3}), the dependence of M_{cr} on r and t is connected with the inhomogeneity and non-stationarity of the external confining pressure P_e and the heating flux determines T_c; $\Phi(M) \propto M^{-\alpha}$, $\alpha > 1$, is the cloud mass function (assumed to be invariant); t_c is the characteristic contraction time; for simplicity, it is estimated as

$$t_c = R_c/(P_e/\rho_c)^{1/2} \tag{10}$$

Then we have

$$\dot{S}_{\mathrm{F}} = \frac{A}{(\alpha-1)\,M_{\mathrm{cr}}^{\alpha-1}} = \frac{A}{\alpha-1}\,\frac{1}{R_c}\left(\frac{P_e}{\rho_c}\right)^{1/2}\left(\frac{\mu^2\,G^{3/2}\,P_e^{1/2}}{k\,T_c^2}\right)^{\alpha-1} \tag{11}$$

To exclude unknown parameters A, R_c, ρ_c and T_c, it is convenient to normalize equation (10) to the unperturbed steady-state SF rate which is assumed to be determined by equation (10) with P_e equal to the unperturbed value P_0. This gives us

$$\frac{\dot{S}_{\mathrm{F}} - \dot{S}_{\mathrm{F0}}}{\dot{S}_{\mathrm{F0}}} = \left(\frac{P_e}{P_0}\right)^{\alpha-1} \tag{12}$$

We will assume that

a) in the steady-state, UV is the main heating source of both intercloud medium and the gas of the absorbing layers of the clouds, and that the absorbing layers and the intercloud gas are in a pressure equilibrium in the unperturbed state (it should be stressed that such assumptions are not essential requirements but are very useful for simplifying a qualitative description of the SF; a more general approach is given by CS);

b) in the disturbed state, after a sudden increase of the UV flux, the variation of pressure at the boundary P_e is described by equation (7).

Under such assumptions, equation (12) can be written as:

$$\frac{\dot{S}_{\mathrm{F}} - \dot{S}_{\mathrm{F0}}}{\dot{S}_{\mathrm{F0}}} = \left(1 + \frac{\delta U}{U_0}\right)^{\beta-1} \tag{13}$$

where δU is the perturbation of the UV flux, U_0 is the unperturbed heating flux, and $\beta = \alpha/2\nu$.

Defining the interstellar UV flux as

$$U(x) = u \int \frac{S(r)\,\exp\left(\tau_0\,(x,\,r)\right)}{|x-r|^2}\,d^3r,$$

where u (photon s^{-1} Hz^{-1} g^{-1}) is the spectral photon luminosity of a single star per stellar mass, $S(r)$ is the mass density contained in the stellar population, $\tau_0 = n_0\sigma_{\mathrm{UV}}|x-r|$ is the optical depth of the averaged interstellar medium to UV photons, n_0 is the mean number density of the interstellar gas, we obtain

$$\frac{\dot{S}_{\mathrm{F}} - \dot{S}_{\mathrm{F0}}}{\dot{S}_{\mathrm{F0}}} = \left\{1 + \frac{1}{4\pi}\,\frac{n_0\sigma_{\mathrm{UV}}}{S_0}\int \frac{\{S\,(r, t-t_0) - S_0\}\,e^{-\tau_0(x,r)}}{|x-r|^2}\,d^3r\right\}^{\beta} - 1, \tag{14}$$

where S_0 is the unperturbed value of $S(r)$ (presumably constant), t_0 is the time interval needed for a protostar to become a main sequence star. To simplify our description, we neglect deviations of interstellar extinction from the averaged value, although such a deviation can be substantial (Savage and Mathis, 1979). It is clear that the stimulating influence of UV radiation on the SF is weaker in those directions which are obscured by dust and, vice versa, stronger in more transparent directions.

Equation of star formation can be written in the following form:

$$\dot{S}(x) = \dot{S}_{\mathrm{F}}(x, t) - t_1^{-1} S(x, t - t_0), \tag{15}$$

where the last term on the rhs describes the spontaneous decay of stars, t_1 is the main-sequence lifetime (we neglect here the spontaneous SF to simplify the analysis of the large-scale feedback which is assumed to be connected mainly with the effects of stimulated SF; the role of the spontaneous SF is analyzed by CS). In this framework, the stationary unperturbed state is described by the equation $\dot{S}_{\mathrm{F0}} = t_1^{-1} S_0$. This allows us to rewrite equation (14) in a more compact form defining new variables

$$\begin{cases} s = S/S_0, \\ r = r/L_{\mathrm{UV}} = r\, n_0 \sigma_{\mathrm{UV}}, \\ t = t/t_1 = t\, \dot{S}_{\mathrm{F0}}/S_0. \end{cases}$$

Using this definition and substituting (14) into (15) we obtain finally

$$\delta\dot{s}(x, t) = \left(1 + \frac{1}{4\pi} \int \frac{\delta s(r, t - t_0)\, e^{-|x-r|}}{|x - r|} d^3 r\right)^{\beta} - 1 - \delta s(x, t - 1), \tag{16}$$

where $\delta s = (S - S_0)/S_0$. Equation (16) is written under the assumption that the mass of the cloud reservoir is constant. This presupposes the existence of mechanisms replenishing the cloud material and in this sense our scheme is not self-consistent. We also assume here that all massive stars included in this scheme have the same mass, i.e., the initial mass function is δ-like, this assumption is usually accepted in earlier models of self-regulating SF. To be specific, we adopt $t_1 = 30$ Myr, corresponding to $M \cong 7 M_{\odot}$. Note that such assumption does not change qualitatively the scenario. On the one hand, stars with $M < 7 M_{\odot}$ are sufficiently less luminous in UV (Kurucz, 1979), and thus they do not influence crucially the SF process in the way proposed above. On the other hand, more massive stars with $M > 7 M_{\odot}$ are more luminous in UV and have shorter evolution time scale. So, excluding these stars from the scheme we underestimate the efficiency of SF.

3.2 Effects of Negative Feedbacks

It is obvious that hard UV or X-ray photons penetrating into the cloud interior can heat the cloud as a whole. CS estimate the lower limit of the energy for the photons to be able to penetrate into a cloud with radius R_c and density n_c as follows:

$$E > 40 \left(\frac{n_c}{10^3\ \mathrm{cm}^{-3}} \frac{R_c}{1\ \mathrm{pc}} \right)^{2/5}\ \mathrm{Ry}.$$

This means that increasing of the flux of hard radiation due to supernova explosions tends to depress SF, and thus acts as a negative feedback in a star-forming system in the way described earlier by Suchkov and Shchekinov (1979) and Parravano (1988). One of the main characteristic features of this mechanism is that the penetrating hard radiation is produced with the time delay t_1 needed for the existing main sequence stars to explode as supernovae. As mentioned by Gerola *et al.* (1980), Shore (1981) and Seiden *et al.* (1982) this time delay can lead by itself to a non-stationary behaviour of SF. In the systems with spatial couplings this provides propagating phenomena (Shore, 1983, Neukirch and Feitzinger, 1988, Korchagin and Ryabtsev, 1989). It is clear that EUV and X-ray photons can support large scale spatial coupling due to a large free path in ISM.

In the framework of our approach, the penetrating heating radiation (EUV and X-rays) leads to a larger critical mass M_{cr} due to a larger cloud temperature: $M_{\mathrm{cr}} \propto T_c^2$. According to equation (9), this results in the reduction of the SF rate $\dot{S}_{\mathrm{F}}$ by a factor $(T_0/T_c)^{2(\alpha-1)}$, where T_0 is the cloud temperature in the unperturbed state (unaffected by EUV or X-rays). At such circumstances, the basic equation of SF is modified as follows:

$$\delta s(x,t) = \left(\frac{T_0}{T_c}\right)^{2(\alpha-1)} \left(1 + \frac{1}{4\pi} \int \frac{\delta s(r, t-t_0)\, e^{-|x-r|}}{|x-r|^2} d^3 r\right)^{\beta} - 1 - \delta(x, t-1). \quad (17)$$

To make the description of SF with depression complete, we need equations of thermal equilibrium of the cloud gas before and after the increase of the flux of the hard heating radiation:

$$\begin{aligned} \Lambda_c(T_0)\, n_c &\propto H_{c0}, \\ \Lambda(T_c)\, n_c &\propto H_{c0} \left\{ (1-\epsilon) + \frac{\epsilon\kappa}{4\pi} \int \frac{(1+\delta s(r, t-1)) e^{-\kappa|x-r|}}{|x-r|^2} d^3 r \right\}, \quad (18) \end{aligned}$$

where $\kappa = \sigma_{\mathrm{X}}/\sigma_{\mathrm{UV}}$, $\sigma_{\mathrm{X}} \cong 6 \times 10^{18}\ \mathrm{cm}^2\ (\mathrm{E/Ry})^{-2.5}$ is the cross-section of EUV and X-ray absorption (see, e.g., Kaplan and Pikelner, 1979); H_{c0} is the unperturbed total heating rate for clouds, and ϵ is the fraction of EUV and X-ray heating. For numerical calculations, the value $E = 0.5$ keV was accepted, which gives $\kappa = 0.4$. [At the limit $\kappa \rightarrow 0$ equations (17) and (18) reduce to equation (14). This happens because the efficiency of the interaction of hard photons with atoms vanishes in this limit.]

3.3 Results and Discussion

An obvious property of equation (14) is that the penetrating heating radiation stimulating the cloud implosion provides a synchronous behaviour of SF on the

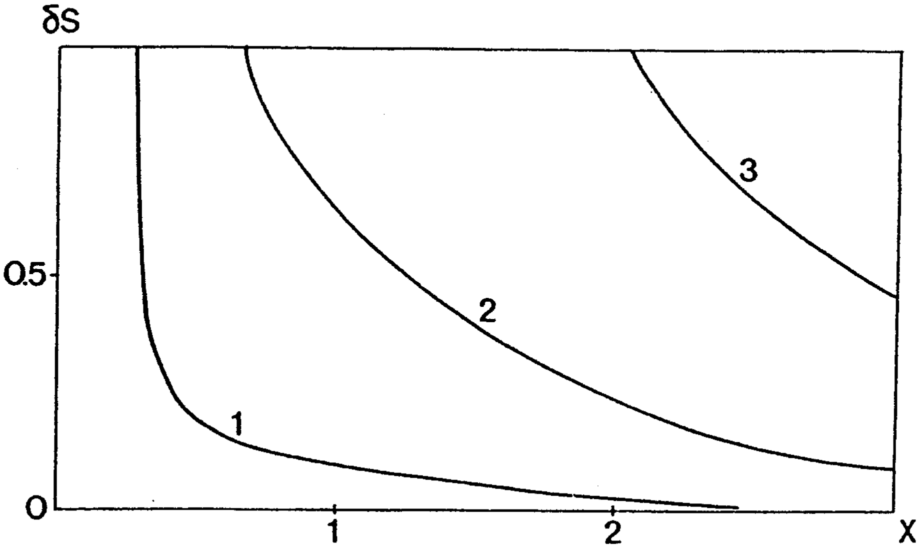

Figure 1 Dynamics of SF in a model with plane symmetry: $\kappa = 0$, $\beta = 1.2$, $t_0 = 1/10$. Initial perturbation is equal $\delta s(0) = 1$ in a cell of size $\Delta x = 0.25$ at $x = 0$. Curves are labeled by values of t.

scales of the characteristic extinction length: this is readily seen from the kernel of the integral equation (14). Due to the fact that $\delta\dot{s}(x,t)$ increases with increasing density of existing stars δs, the integral on the rhs of equation (14) describes a large-scale positive feedback. The characteristic value of the velocity of the spreading SF process can be estimated as a ratio of the extinction length to the time of the formation of a star from a protostellar cloud: $U_{\rm SF} \sim L_{\rm UV}/t_0 \sim$ 100–1000 km/s for $L_{\rm UV}$ accepted above and $t_0 \sim 10^6 - 10^7$ yr. This regime corresponds to the starburst mode. On the other hand, hard radiation for which clouds are transparent provides a large-scale (with the characteristic scale $L_{\rm X} = L_{\rm UV}/\kappa$) negative feedback because it increases the denominator of equation (17) due to increasing of T_c (see equation (18)). The main difference of the systems described by equation (14) on the one hand and by equation (17) and (18) on the other is that in the first case the dynamics of SF is controlled by the positive feedback resulting in progressive SF covering ever-growing regions. In the second case, there are two different regimes depending on the ratio of $L_{\rm UV}/t_0$ to $L_{\rm X}/t_1$. In the case $(L_{\rm UV}/t_0) > L_{\rm X}/t_i$ or in equivalent form $\kappa > (t_0/t_1)$ the wave of star, formation caused by positive feedback spreads over the system at a larger velocity than the depression wave caused by the negative feedback. In an ideal case this looks as a ring of SF edging a "hole" with quiescent or depressed SF. In another limit of $0 \ll \kappa < (t_0/t_1)$ the starburst mode can be changed into a global inhibition of SF. In this case the wave of depression of SF can overtake the self-exciting SF wave formed at the previous stages. If the fraction of X-ray heating is quite large, $\epsilon \sim 1$, this can result in the ceasing of the self-propagating SF process. The characteristic size of the region corresponding to

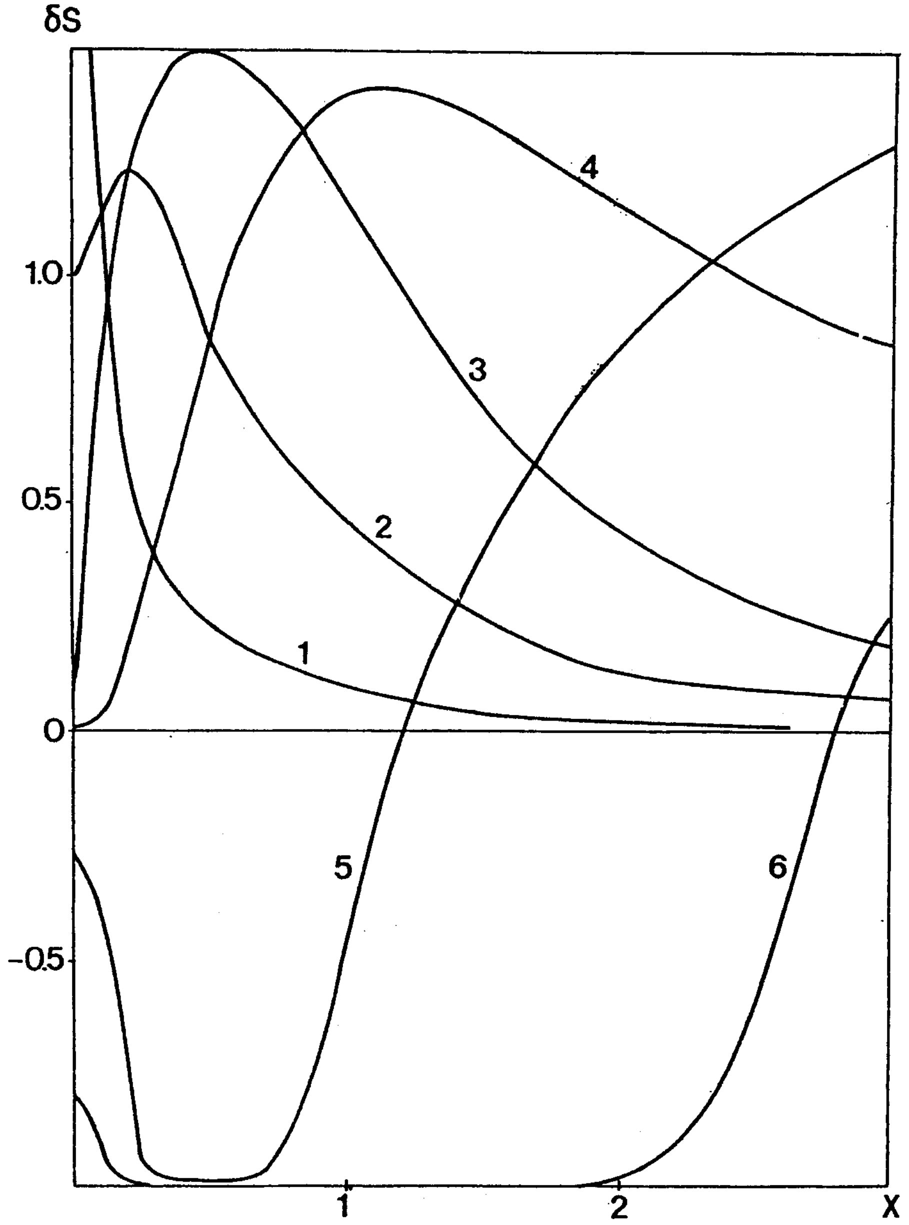

Figure 2 Same as in Figure 1 with inhibition of SF by fast radiation: $\kappa = 0.4$, $\epsilon = 0.1$.

such overlapping is estimated as $\sim L_{\mathrm{UV}} t_1/t_0(1-\kappa)$, and for the accepted values of parameters ($L_{\mathrm{UV}} \sim 1$ kpc, $\kappa = 0.4$ and $t_1/t_0 \sim 1$) it is of the order of ~ 2.5 kpc. In this framework we are allowed to think that the overlapping of the regions of the positive and negative feedback determines the size of self-excited starbursts.

Here we discuss in short numerical results demonstrating global synchronous dynamics of SF regulated by heating radiation. Figure 1 shows temporal behaviour of SF excited by a δ-like perturbation of s at $x = 0$ for plane-parallel symmetry, $\kappa = 0$, $\beta = 1.2$, $t_0 = 1/10$ and $\delta s(0) = 1$. At initial stages, a perturbation of stellar density of a fixed value (e.g., $\Delta S \sim 0.5 S_0$) covers the range of $\delta x \sim 1$ during the time $\Delta t \sim 1$, so that $U_{\mathrm{SF}} \sim 1$, or in dimensional form $U_{\mathrm{SF}} \sim L_{\mathrm{UV}}/t_1$. For interstellar medium with the mean density $n \sim 0.2$ cm^{-3} and $t_1 = 3 \times 10^7$ yr this gives $U_{\mathrm{SF}} \sim 25$ km/s. Later, at $t > 3$, the value of U_{SF} increases and tends to its asymptote $U_{\mathrm{SF}} \sim L_{\mathrm{UV}}/t_0 \sim 250$ km/s. One of the results of numerical calculations is approximate proportionality of the solution $\delta s(x,t)$ at given x and t to the amplitude of initial perturbation $\delta s(0)$. This is due to weak non-linearity effects in equation (16) for $\beta = 1.2$.

Figure 2 demonstrates the dynamics of a star forming system with self-regulation by both positive and negative feedbacks: $\kappa = 0.4$, $\beta = 1.2$, $t_0 = 1/10$, $\epsilon = 0.1$, and $\delta s(0) = 1$. This model corresponds to the case $\kappa > t_0/t_1$ with the SF wave passing ahead of the wave of the depression of SF. As in previous model, the velocity increases from $U_{\mathrm{SF}} \sim 1$ at initial stages to its asymptotic value $U_{\mathrm{SF}} \sim 10$. For particular values of parameters of this model the intensity of hard radiation is quite large to suppress SF completely in the region covered by the depression wave.

The models with comparable t_0 and t_1 are more complex dynamically (for detailed description see CS). This is connected with the fact that for $t_0 \sim t_1$ it is difficult to separate the effects of positive and negative feedbacks, and moreover, the interaction of the starburst mode excited by the positive feedback with the depressing mode connected with the negative feedback provides oscillating regimes of SF. But in any case the above mentioned tendency of the depression wave to cease starburst at a certain critical size of starbursting region is unquestionable. This is demonstrated by Figure 3, where numerical results for the model with $\kappa = 0.4$, $\beta = 1.2$, $t_0 = 1/2$, $\epsilon = 0.1$ and $\delta s(0) = 1$ are presented for $t \leq 4$, the stimulating effects enhance SF (by about 15–20%) in the region with the size ~ 3, and then the depression wave overtakes the SF region and ceases the starburst.

4 CONCLUSIONS

At present there are two basic theoretical conceptions explaining the star-forming activity of galaxies and their constituents: the tidal interactions of galaxies and the self-exciting SF operating due to induced star formation effects. Previous models dealt with the induced SF caused by short-range action of shock waves from supernovae, stellar winds or HII regions. As a consequence, a wave-like SF mode was explained in this framework, while asymptotically this short-range mechanism can create grand-design structures in parents galaxies (Neukirch and Feitzinger, 1988;

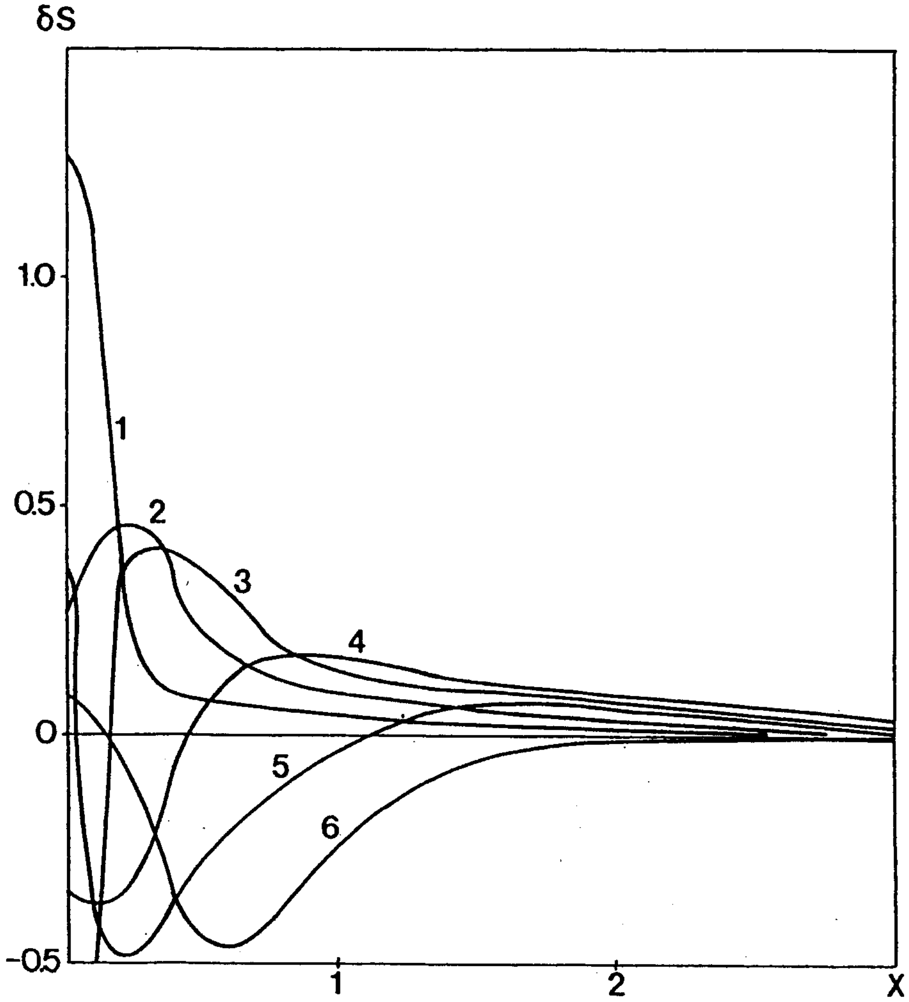

Figure 3 Same as in Figure 2 with $t_0 = 1/2$.

Nozakura and Ikeuchi, 1988; Korchagin and Ryabtsev, 1992). At the same time, burst-like star formation phenomena require the existence of large-scale forces which would be able to maintain coherent behaviour of SF on galactic scales with a short characteristic time. For interacting galaxies, tidal forces are the most natural generator of starbursts, but while speaking about starbursting isolated galaxies it is necessary to assume an internal mechanism able to synchronize SF over the whole galaxy on a short time scale.

We have demonstrated here that the stimulation of SF by stellar heating UV radiation ($\lambda > 912$ Å) has the features of a large-scale synchronous SF with the characteristic size of $L_{\rm UV} = (n\sigma_{\rm UV})^{-1} \sim 1$ kpc. It is obvious that the mechanism proposed is more efficient in galaxies with high gas-to-dust ratio, like the LMC where reddening per unit HI column density is about a quarter of the value typical of the Galaxy (Korneef, 1983). Actually, L_{UV} is the scale of coherency of SF because the differences of the stellar ages separated in space by L_{UV} are less than the main-sequence life time: $t_0 < t_1$. It allows us to think that this mechanism can dominate (or at least play a certain role) in star forming systems observable as starbursting ones.

Large-scale negative feedback connected with heating of interstellar clouds by hard penetrating radiation (EUV or X-rays) depresses SF and results in ceasing of SF or creation of "holes" with quiescent SF surrounded by starbursting regions depending on characteristics of EUV and X-ray absorbtion, the efficiency of EUV and X-ray heating, the time scale of the conservation of clouds into stars. It is appropriate here to mention the paper by Greggio *et al.* (1992) where the SF history in irregular galaxies DDO 210 and NGC 3109 during the last 1 Gyr is described as a long episode of moderate SF activity with short periods of quiescence. It would be very suggestive to interpret such behaviour as a result of regulation by the negative feedback proposed above.

One of the mechanisms of positive feedback on intermediate scales has been described by Shchekinov (1992). The main idea is based on the fact that a cumulative wave compressing a cloud can be driven by thermal conductivity as well. The specific mechanism of conductive driven cloud implosion is quite similar to the mechanism of photoimplosion described in Section 2: for a cloud embedded into a hot gas with $T \sim 10^6$ K, thermal conductivity generates at initial time an excess of pressure at the cloud border, which excites both compression and evaporation flows. At appropriate conditions, the compression wave can stimulate the cloud collapse (Kovalenko and Shchekinov, 1992; Ferrara and Shchekinov, 1993). So, a hot environment can be a factor of stimulation of SF. At such circumstances, it is permissable to assume that tenious tunnels of hot coronal gas (Cox and Smith, 1974; McKee and Ostriker, 1977) stimulate SF inside the immersed clouds. Shchekinov (1992) has supposed that such a mechanism creates a region of starburst with a size of 1–3 kpc. One could assume that such regions represent the star-gaseous structures described by Efremov as stellar complexes (Efremov, 1989). But such an assumption requires an additional investigation. It is quite possible that conductively induced SF can play a certain role in starbursting galactic nuclei.

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