STAR FORMATION REGIONS AS GALACTIC DISSIPATIVE STRUCTURES

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Abstract. The theory of dissipative structures, applied to star formation systems, provides a conceptual framework for the study of the behaviour and evolution of these systems. As shown by an analysis of a model star formation process system, prolonged stationary star formation in localized areas and repetitive bursting star formation events can be understood as different behavioural modes of galactic dissipative structures. Young stellar associations with their H II regions and molecular clouds are manifestations of the ordered distribution of matter participating in the star formation processes. A self-organization with the appearance of ordered structures is, in general, to be expected in nonequilibrium systems in which nonlinear processes occur. However, lacking a thermodynamic theory that can be applied to self-gravitating systems, the behaviour of star-forming regions can only be studied by model calculations simulating the process system within the region.

1. Introduction

The spatial distribution of star formation in a galaxy is not uniform but concentrated in a number of localized areas, usually of small size with respect to the galaxy. Evidence for bursting star formation in many galaxies suggests that the temporal behaviour, too, may be non-uniform. These observations show that star-forming regions are manifestations of a spontaneous galactic self-organization, in which matter and energy acquire structured distributions in space and time, that deviate considerably from the stable and homogeneous situation to be expected, in general, under equilibrium conditions.

It is known that structure and orderly behaviour in macroscopic nonconservative systems can arise as a consequence of nonequilibrium conditions that drive irreversible processes. Under certain circumstances, entropy producing processes are able to organize themselves in the presence of noise, in such a way, that so-called 'dissipative structures' are formed (Glansdorff and Prigogine, 1971; Prigogine and Lefever, 1975; Nicolis and Prigogine, 1977). In these structures a functional order is present that manifests itself by a cybernetically stabilized spatial and temporal organization of the system.

Necessary conditions for the occurrence of dissipative structures are, that the system is open, that it is in a state far from thermodynamical equilibrium, and that nonlinear processes occur within the system. In these conditions, internal small fluctuations may be amplified nonlinearly by the processes that are fed by a flow of mass and energy from the surroundings. The system is then removed irreversibly from its initial state, in particular from any homogeneous or unorganized state that is characteristic for equilibrium conditions. Therefore, the new state is characterized by a more organized internal distribution of matter, energy and process rates. As long as there is a supply

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of free energy and as long as the removal of entropy and waste products is possible, the system evolves in such a way that eventually a state of organization is reached that has a certain degree of stability.

Galaxies show different kinds of chemical and structural organization, some of it directly related to star formation processes. Molecular clouds and associations of young stars are nonequilibrium structures found in all star-forming galaxies that seem to be sustained over much longer time periods than the time-scale of their possible dissolution by chemical, kinematical, or stellar evolution processes. The clumpy nature and inhomogeneities of the interstellar medium and young stellar populations should be studied, therefore, in the framework of the theory and models of dissipative structures.

In this paper it is argued that galactic and extragalactic star-forming regions are giant dissipative structures, stabilized by their internal process systems. In Section 2, observational evidence indicative for prolonged and self-sustained star formation is discussed. In Section 3, it is argued that the structural properties of star formation regions point towards an internally regulated organization. In Section 4, the system components and mutually interconnected processes responsible for the self-organization are identified. In Section 5, some theoretical considerations and results of a stability analysis of a model star formation process system are presented.

2. Star Formation Regions: Stability of the Process System

Since Trumpler (1925) emphasized the importance of HR diagrams of open clusters to study cluster ages, it is generally assumed that the members of a cluster originated at almost the same time. However, turn-off points tend to give only a lower limit for the cluster age, and in principle, large spreads in ages of member stars cannot be excluded. Considerable spreads, at least on a time-scale characteristic for very young clusters, have been established, indeed, for a number of OB associations.

Doom *et al.* (1985) determined stellar ages in Per OB1 and Cen OB1 among others on the basis of evolution tracks that take into account the effects of mass loss and convection overshooting. They found systematic spreads in age that cannot be attributed to selection effects. In both associations, stars of all ages less than 30 million years are present. Moreover, a relation is observed to exist between initial stellar mass and stellar age; the most massive stars always being formed last. Ages of stars with masses of 20 $M_\odot$ or more define the minimum age of the cluster.

This shows that, within every association investigated, star formation must have been going on for at least several tens of millions of years. Figure 1 gives the initial mass versus age diagram of the four subgroups of the Ori OB1 association (Doom, 1985; unpublished data). For the subgroups b, c, and d a spread in stellar age of at least 20 to 30 million years can be noted. Older stars may be present but are beyond the reach of the method. Therefore, it is possible that subgroup a, too, has a large age spread but this cannot be concluded from existing data. Similar relations between the initial stellar mass and stellar age are also found in the subgroups of the Per OB1 association.

The spread in age of the associations is not caused by the presence of subgroups with

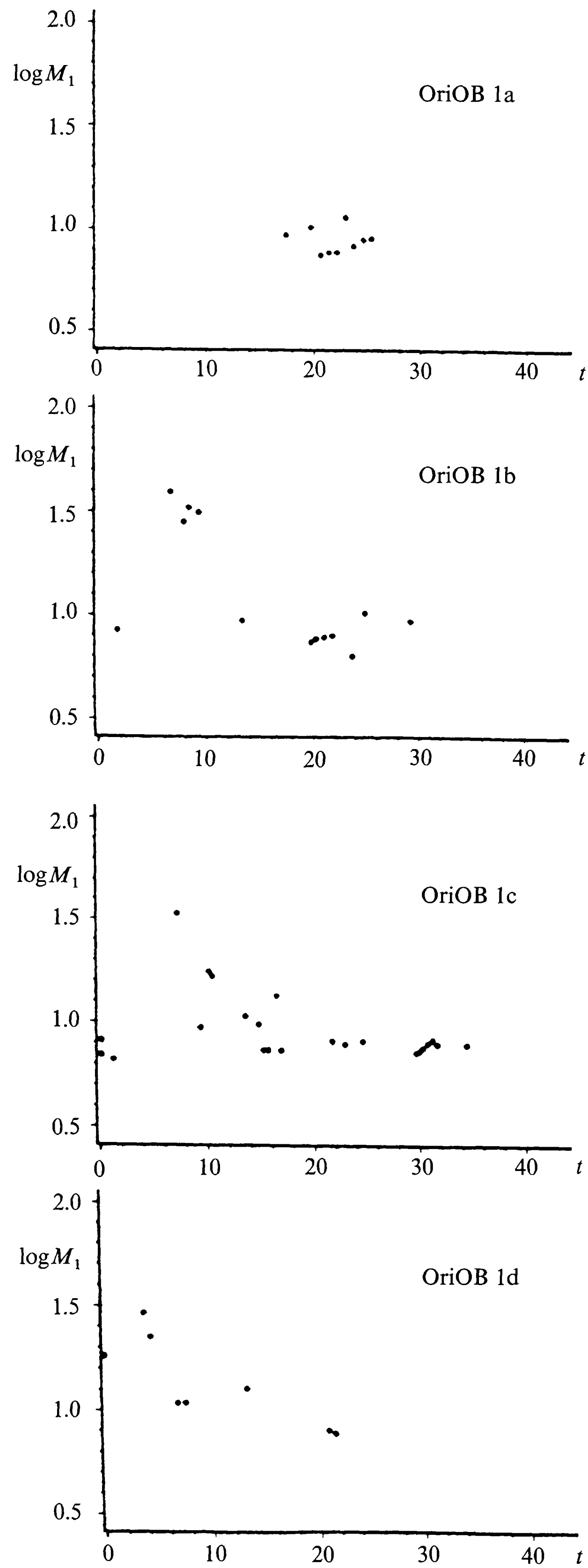

Fig. 1. Age diagrams of the four subgroups of Ori OB1 (Doom, 1985). The ages t are in million years, the initial masses M_i of the member star in solar masses.

different ages, since similar and overlapping spreads are found within the different subgroups. Rather, it seems that the subgroups have undergone parallel evolutions of continuing star formation, although they probably have different minimum ages. In the case of Ori OB1, subgroup a must be the oldest, with an age of 16 to 24 years for its most massive stars, while star formation is still going on at this moment in subgroup *d*. Apart from a few stars with seemingly abnormal low ages, whose membership of their respective subgroups is tentative, subgroups *b* and *c* seem to hold a position in between *a* and *d*.

Intuitively, the interruption of the star formation process could be explained as a consequence of exhaustion of the local gas supply, or a disruption of the parent molecular cloud by the energetic outflows of the massive stars, but this problem will not be discussed here. In this paper, the fact of the continuation of star formation over prolonged periods of time is emphasized. Contrary to a widespread assumption that the members of an association, or a subgroup, are born at about the same time, it must be concluded and is to be explained, that associations or their subgroups are locations of ongoing star formation for periods of at least several tens of million of years. It cannot be derived from the techniques used by Doom and his collaborators, if the star formation rate has been constant during an association's history, or if there have been long-term trends, fluctuations or oscillations. The results show only that the rate drops to zero when stars are formed with masses larger than approximately 20 $M_\odot$.

These findings prove that the star formation process, once started, does not exhausts the available material in a runaway collapse, but manages to regulate its rate (except when the most massive stars are born). The conclusion of a low-efficiency star formation is in agreement with results of other independent investigations (only 0.2–0.3% in the λ Ori OB association, according to Duerr *et al.*, 1982). The sustained star formation process system possesses a certain stability that must be the result of some kind of regulation. A continuous supply of interstellar gas, replenished by inflow or cooling of hot intercloud gas, feeds the process but, probably, is only part of the regulating mechanism.

Other observational evidence exists for prolonged star formation activity in localized regions. From Hβ line width measurements of the giant H II regions NGC 595 and NGC 604 in the Sc spiral M33, Hunter and Gallagher (1985) find evidence for the presence of evolved massive stars in these regions, from which they infer that the star formation has continued over several O-star generations. It is interesting to note that both H II regions contain multiple subgroupings of stars or compact clusters, but it is not known if the ongoing star formation proceeds simultaneously or sequentially in these substructures.

Particularly interesting are observations of the stellar contents of 30 Dor in the LMC. On the basis of 2 μm infrared observations of the core of this H II region, Hyland *et al.* (1978) conclude that there is a large population of red supergiants with masses of 15 to 20 M_0. These stars must have ages of approximately 10 million years. From the presence of these stars and another population of blue supergiants in the same area, they conclude that at least two bursts of star formation occurred in 30 Dor in the recent past.

The last burst took place about 3 million years ago, the previous one 7 million years earlier. From the intensity of the Lyman continuum and the far UV flux, Lequeux *et al.* (1981) infer an age of between 0.6 and 2.5 million years for the most recent burst. This is in good agreement with the age of 2 million years, derived by Dottori and Bica (1981) from the equivalent width of the Hβ emission line. From infrared photometric observation McGregor and Hyland (1981) conclude that two star bursts took place in 30 Dor during the last 50 million years, confirming the earlier findings. The most recent burst would be less than one million years old, according to these authors.

These observations suggest a repetitive character of the star formation activity in this region, and offer evidence for an oscillatory character of the prolonged activity.

In many cases, star formation regions are found to lie along linear chains, spatially ordered according to age, indicating a long-continued star formation process of which the centre of activity has moved gradually in time. Some striking examples in our Galaxy are the W3–W4–W5 radio sources associated with the H II regions IC1795, IC1805, IC1848, and the association Cas OB6 (Sullivan and Downes, 1973; Wendker and Althenhoff, 1977; Thronson *et al.*, 1980a, b), the H II-molecular complex M17 (NGC 6618) (Thronson and Lada, 1983; Felli *et al.*, 1984), the Orion nebula M42 with the molecular cloud OMC1 and the association Ori OB1 (Warren and Hesser, 1977a, b, 1978; Zuckerman and Palmer, 1974), the radio source W58 with its various H II regions, masers and clouds of neutral gas and dust (Israel, 1976), W51, a complex of H II regions, molecular clouds and infrared sources (Mufson and Liszt, 1979; Lightfoot *et al.*, 1983).

These examples show that star formation is a stable self-regulated process, proceeding at a more or less stationary or oscillatory rate, for time periods that are considerably longer than OB star lifetimes or the estimated lifetime of molecular clouds (Blitz and Shu, 1980). The process organizes itself in localized centres of activity that can move and change positions over tens or hundreds of parsecs, while retaining their identity as distinct star formation systems. The activity can proceed at either a more or less continuous rate, or it could be a series of successive star formation events.

3. Star Formation Regions: Morphological Similarities

The physical appearance and structural properties of giant extragalactic H II regions have been discussed recently by Kennicutt (1984) and Hunter and Gallagher (1985). While there is considerable diversity in size, luminosity, mass and density of H II regions, many basic properties tend to be similar. Important structural and morphological parallels are observed among giant H II regions in galaxies of different types, such as 30 Dor in the LMC, NGC 604, and NGC 595 in the Sc spiral M33, several H I–H II association in the Sc spiral M101 (Viallefond *et al.*, 1982), large star formation complexes in the irregular galaxy NGC 4449 (Hunter, 1982) and blue compact galaxies. Smaller star formation regions, as found in our Galaxy and M31, also show similar contents and configurations. Also, the peculiar ellipticals NGC 185 and NGC 205 contain localized star formation complexes with basically similar characteristics (van den Bergh, 1975; Gallagher and Hunter, 1981).

The common structural pattern of these star formation regions is that of a group of young stars, often with multiple centers, embedded in a nebula of ionized gas, consisting of a dense core, mostly surrounded by an asymmetric and diffuse halo, and with a massive molecular cloud. In galactic OB associations a substructure can be recognized in a number of cases (Blaauw, 1964; Blitz and Thaddeus, 1980). Despite a large diversity in sizes and luminosities, H II regions possess surprisingly similar density profiles, although the giant extragalactic H II regions have more extended envelopes (Kennicutt, 1984). H II regions always lie in the immediate vicinity of dust-rich molecular clouds with densities of 10^4 molecules per cm^3 or more (Loren, 1981; Snell, 1981; Vanden Bout *et al.*, 1983). Often, it is observed that the diffuse ionized gas is bounded sharply on one edge, adjacent to the associated molecular cloud, and extends to large distances in the opposite direction (Israel *et al.*, 1982; Viallefond *et al.*, 1983). From internal extinction and infrared emissions, the presence of dust intermixed with both the neutral and the ionized components is inferred (e.g., Melnick, 1979; Stein and Soifer, 1983). H II complexes always are associated with a concentration of neutral hydrogen (Israel and van der Kruit, 1974; Newton, 1980; Viallefond *et al.*, 1982) with a mass comparable to the molecular cloud mass. On small scales, H II regions are extremely inhomogeneous. Filamentary structures and clumping dominate their morphology (Blitz and Thaddeus, 1980). The mean filling factor of most regions, from the smaller galactic to giant extragalactic H II regions, fall within the rather narrow range of from 0.1 to 0.01 (Kennicutt, 1984).

The physical appearance and gas dynamics of the ionized regions have been explained by the champagne (Tenorio-Tagle, 1979) or blister model (Israel, 1978), and by models of stellar wind blown bubbles (Rosa and Solf, 1984; Dorland *et al.*, 1985). According to the champagne and blister models, we see in H II regions advanced stages of star formation, taking place near one end of a dense molecular cloud. The ionization fronts are eating into the neutral cloud, while the bulk of the ionized material streams away from the cloud.

In this paper, these models will not be discussed further, but it is argued that the structural and morphological similarities of H II regions in galaxies of different types suggest that physical processes intrinsic to star formation regions dominate over influences due to galactic environments in controlling the evolution of these regions. Internal process dynamics, not external conditions, determine the structural properties of star formation regions. In some cases, star formation may be stimulated by external agents, such as the effects of close tidal interactions or collisions between galaxies, but well developed H II regions and other signs of vigorous star formation are observed, too, in many isolated galaxies. Bursts of star formation are probably observed in blue compact galaxies (Huchra, 1977; Lequeux *et al.*, 1979). In some of them, tidal interaction may be responsible (e.g., in IIZw70, O'Connell *et al.*, 1978) but there are isolated dwarf galaxies (e.g., IIZw40) undergoing similar bursts. Clearly, internally triggered, sustained and organized star formation occurs in many galaxies, isolated or not, over a wide range of galactic sizes and Hubble types.

It may be concluded that the star formation process is able to proceed in an autonomous way, more or less independent of external perturbations and, to a large extent, of its galactic environment. The star formation concentrates in localized areas, where nonhomogeneous and structured conglomerates of H I, H II, molecular gas, and young stars are produced during the process.

4. Process System

In order to study the self-organizational capability of star-forming galaxies, the mass transformation, exchange and transport processes that constitute the star formation process system must be understood.

Relevant information for the identification of the components and processes involved follows from observational data mentioned in Section 3. There is compelling evidence that stars form only in places that are rich in dense and dusty molecular gas, the neutral molecular clouds being embedded in neutral atomic gas. Hence, young stars with their associated H II regions, cool molecular and atomic gas must be components of any model star-forming system.

Two different star formation modes must be discerned: the birth of stars can occur in a spontaneous or triggered way. Various mechanisms could be responsible for the triggering, such as supernova explosions (Öpik, 1953; Krebs and Hillebrandt, 1983), ionization fronts and shock waves emitted by early-type stars (Elmegreen and Lada, 1977; LaRosa, 1983), and stellar winds from OB stars that increase the intensity of the shock waves produces by the expanding ionization fronts (Elmegreen and Lada, 1977; Elmegreen and Elmegreen, 1978). In any case, triggering of star formation is a consequence of the transport of radiative and kinetic energy from young stars to the interstellar medium. Triggered star formation should be considered, therefore, as a kind of autocatalysis, whereby young stars produce more young stars.

External perturbations, such as density waves or galactic tidal interactions, may play a role in modulating the rate of both modes of star formation, but should be considered probably only as a secondary effect on essentially internally regulated processes, except in places where the external perturbations are of overwhelming force. The relative importance of spontaneous and triggered star formation is difficult to estimate but the indications are that star formation triggered by previously formed stars is a common phenomenon, at least for massive stars, since isolated star formation seems to be rare (Habing and Israel, 1979). At least one example of apparently spontaneous star formation is known, however. The maser-source ON1 is an isolated ultracompact H II region (Winnberg *et al.*, 1973) that shows many signs of active star formation: there are a few B stars, various molecular masers and infrared sources. The region is isolated in the sense that no other H II regions are present within a distance of several parsecs (Harris, 1974; Matthews *et al.*, 1977). It is not clear, at this moment, if the rareness of spontaneous star formation is a real phenomenon or an observational selection effect. Many indications exist for the widespread occurrence of triggered star formation. The examples of sequentially-ordered star formation regions, mentioned in Section 2, leave no doubt that triggering mechanisms are in operation.

It may be concluded, therefore, that stimulated star formation is an important positive feedback mechanism in operation in all star-forming regions. Other process couplings with positive feedback exist, moreover, in the star formation process system.

Molecular clouds are characterized by low temperatures (10 K for the dense parts) that are a consequence of efficient cooling mechanisms (Goldsmith and Langer, 1978) and molecular shielding of background stellar ultraviolet radiation. The cooling agents are able to remove heat produced from many sources, such as gravitational collapse, high-energy cosmic rays and chemical reactions. By their vibrational and rotational transitions, many molecular species are more efficient radiators than free atoms for the removal of heat form the cloud. Internal velocity fields within the cloud add to this capability since the Doppler shifts prevent rapid line saturation. The presence of grains, essential for the formation of H_2 molecules, may also be important for the cooling of the cloud. According to Scalo (1977), dust cooling is the dominant mechanism in clouds with a density of more than 10^4 cm^{-3}. The exclusion of stellar radiation by molecular shielding also removes an important heat input to a cloud from UV radiation and the photoelectric effect.

Because of these ways to remove or prevent the accumulation of internal energy, molecular clouds are able to collapse more easily than clouds of atomic, dust-free gas. The increased density, then, accelerates chemical reactions within the cloud, leading to a higher molecular production yield and to improve shielding against radiative dissociation.

Hence, the presence of molecules in the interstellar medium leads to a further production of molecules, implying the possibility to generate nonlinear growths of inhomogeneities and density perturbations. Model calculations by Oppenheimer and Dalgarno (1975) showed, indeed, that the chemistry of a cloud may serve as a nonlinear amplifier of density fluctuations.

Metal-enhanced star formation is another positive feedback effect that may play a role. Local metal-enrichment of the interstellar medium by young stars may increase the star formation efficiency if the time-scale of chemical homogenization over galactic distances is considerably larger than that of the collapse processes. Because of their inability to spread or remove material easily, galactic nuclei may be sites where this effect is of some importance.

The working of positive feedback mechanisms severely destabilizes the process system, always threatening to provoke a runaway evolution until complete exhaustions of the system's resources. Negative feedback effects, provided by diminishing gas supplies as a consequence of gas enclosure in stars, heating and dispersal by stellar emissions and insufficient replenishment, can compensate and tend to keep the system back under control. Franco and Cox (1983) already suggested that the negative feedback caused by the local disruption after a high stellar birthrate can lead to a self-regulated star formation rate.

The combined effects of the cross-coupled and auto-coupled processes of a star formation region can enable the system to behave in a dynamically intricate way, fundamentally different from the predictable stable rates of simple and linear processes as, for example, in near-to-equilibrium reaction kinematics. Instead, the behaviour of a complex system can be dominated by small stochastic fluctuations that are nonlinearly amplified and that cause bifurcations to arise in the solutions describing the system's state. It is in this way, that the dynamic and evolving behaviour of a dissipative structure may emerge. New forms of organization then arise, whereby non-uniform mass distributions and coherent behavioural regimes are realized that deviate considerably from possible equilibrium solutions. A functional order is created then, in which the system settles itself in a more or less stable regime, actively sustained by the processes running inside.

This kind of self-organization is possible only in the presence of a permanent non-equilibrium that drives the irreversible processes. In a galactic context, the condition of far-from-equilibrium conditions is always fulfilled. The self-gravitation of cosmic systems prevents them from reaching a state of equilibrium. At the same time, intergalactic space is an unsaturable sink for waste radiation produced by the dissipative processes. This fortunate situation may be related to the present expansion of the Universe, with no equilibrium between matter and radiation, but it may also be a consequence of the mere size of the Universe, preventing it from being saturated with starlight (Harrison, 1984). In any case, the radiative nonequilibrium of the Universe allows dissipative processes and self-organization of matter to go on.

With the ever availability of a source (gravitation) and a drain (radiation), a galaxy experiences a permanent throughflow of energy, that is canalized into regions of star formation through the functional order acquired under process feedback control.

5. Theoretical Considerations

A criterion for the occurrence of dissipative structures under conditions of local equilibrium but global nonequilibrium was derived by Glansdorff and Prigogine (1971). It states that stability of the stationary state of a process system is not guaranteed when

$$\frac{\mathrm{d}}{\mathrm{d}t}\,(\delta^2 S) < 0\,, \tag{1}$$

where $\delta^2 S$ is the second-order perturbation of the entropy of the system, that is shown to be equal to the sum of the products of thermodynamic fluxes and forces. However, this criterion cannot be applied to astrophysical systems where gravitation is a dominant force. As is well known, gravitation makes the specific heat of a system negative, and this leads to a positive sign for the second-order perturbation of the entropy

$$\delta^2 S = \frac{\partial}{\partial Q}\left(\frac{\delta Q}{T}\right)\delta Q = -\,\frac{\delta T}{T^2}\,\delta Q > 0\,. \tag{2}$$

The Glansdorff–Prigogine criterion is based on the fact that in a stable thermodynamic system $\delta^2 S$ is a Lyapunov function, since its sign is definite negative, while that of its time derivative is positive. However, in the presence of both gravitation and dissipation the sign of $\delta^2 S$ is indefinite and it no longer determines stability.

Since it can always evolve towards a state of less potential energy, a self-gravitating system possesses in principle an unlimited reservoir of free energy, and it never reaches equilibrium. Even if the system is virialized or otherwise supported against collapse, no true equilibrium has been achieved. At the same time the low radiation temperature of intergalactic space is an ideal thermodynamic sink. Hence, as stated in Section 4, the conditions for permanent throughflow and dissipation of energy are available, and the occurrence of dissipative structures is, therefore, to be expected in places where feedback couplings of the processes make them behave nonlinearly.

The temproral behaviour of a galactic star formation region can be studied by adopting process equations that describe the interchanges between the different components of the system. In the absence of a general theory, this approach may reveal typical behavioural modes of particular model systems. The introduction of macroscopic variables representing large-scale galactic properties such as densities of various components is then necessary. Interactions between these variables have to be formulated without taking into account the microscopic mechanisms underlying these interactions. In many cases, these mechanisms may not even be known, or it may be impossible to derive the macroscopic behaviour from the basic processes. In order to define the variables and their relations, it is necessary to identify the essential ingredients of a star formation system, and to characterize the processes that occur within the system. Much of this information is included in the data discussed in Sections 3 and 4.

For a galactic system of n components that exchange mass through mutual interactions, a system of n coupled differential equations must be written as

$$\frac{\partial X_i}{\partial t} = F_i(X_1, \ldots, X_n) + G_i(X_i) \quad (i = 1, \ldots, n) . \tag{3}$$

The functions F_i are nonlinear functions of the masses X_i of the different components. They describe the transformations that result form the various processes and mass exchanges between these components. The functions G_i are transport terms that represent the local density variations of the components, induced by transportation processes, such as diffusion, bulk mass motions and galactic differential rotation. If the system is sufficiently small that it can be considered spatially homogeneous and no large-scale galactic motions influence its internal processes, G_i may be cancelled and Equations (3) describe the local evolutions of the concentrations of the components as a function of time.

By their nonlinearity, Equations (3) have in general many different stationary or time-dependent solutions, that may be stable or not. This allows for a variety of physical phenomena and behavioural patterns, such as regular or chaotic oscillations. Equations (3) are analogous to the reaction-diffusion equations that are used to study the dynamics and pattern formation of chemical reaction systems (e.g., Mielczarek *et al.*, 1983; Albano *et al.*, 1984).

More specifically, a star formation region can be modeled by the following system of equations:

$$\frac{dA}{dt} = K_1 S + K_2 S - K_3 M^2 A , \tag{4a}$$

$$\frac{dM}{dt} = K_3 M^2 A - K_4 S M^n , \tag{4b}$$

$$\frac{dS}{dt} = K_4 S M^n - K_1 S - K_2 S , \tag{4c}$$

$$\frac{dR}{dt} = K_1 S ; \tag{4d}$$

in which, A, M, and S are the masses of the interstellar atomic gas, the interstellar molecular gas (with dust), and the stellar material (young stars with their associated H II regions) within the system. R represents the total mass of 'old' stars (stellar remnants and low-mass Main-Sequence stars). The values of the time-independent parameters K_i are determined by mostly unknown details of the physical and chemical processes involved. The whole process system amounts to an irreversible transformation of atomic gas into old stars, fed by gas from the surroundings (the supply reservoir) and producing compact conglomerates of degenerated material, in which mass is burried indefinitely (waste reservoir). Clouds of atomic and molecular gas and young stars are the active components that participate in the processes by mutual interactions and mass exchange. Figure 2 illustrates the overall structure of the process system. The influx of gas from the surroundings (indicated by the arrow labeled 1 in the figure), is put equal to the rate of transformation of young stars into old stars (arrow 2) that removes the mass essentially from the system (terms $K_1 S$ in Equations (4a) and (4d)). In this way, the whole system possesses a constant mass. Stellar mass loss and recombination of ionized gas are pictured by arrow 3, production of molecular gas from atomic gas by arrow 4 ($K_3 M^2 A$), and triggered star formation in molecular clouds by arrow 5 ($K_4 S M^n$), where n is an index between 1 and 2. The system is driven by gravitational energy and the emission of thermal radiation.

After elimination of S and the introduction of dimensionless variables, the equations can be written as

$$\frac{da}{d\tau} = 1 - a - m - k_1 m^2 a , \tag{5a}$$

$$\frac{dm}{d\tau} = k_1 m^2 a - k_2 m^n + k_2 m^n a + k_2 m^{n+1} ; \tag{5b}$$

where a and m are the fractional masses of atomic and molecular gas, and τ is a dimensionless time variable; $\tau = (K_1 + K)t$; k_1 and k_2 express, respectively, the efficiency of production of molecules and of the efficiency of triggered star formation. It is found that the process system described by Equations (5) can settle into three possible stationary states, two of them trivial (all mass contained into either atomic or molecular gas), depending on the values of the parameters k_1, k_2, and n. The non-trivial stationary

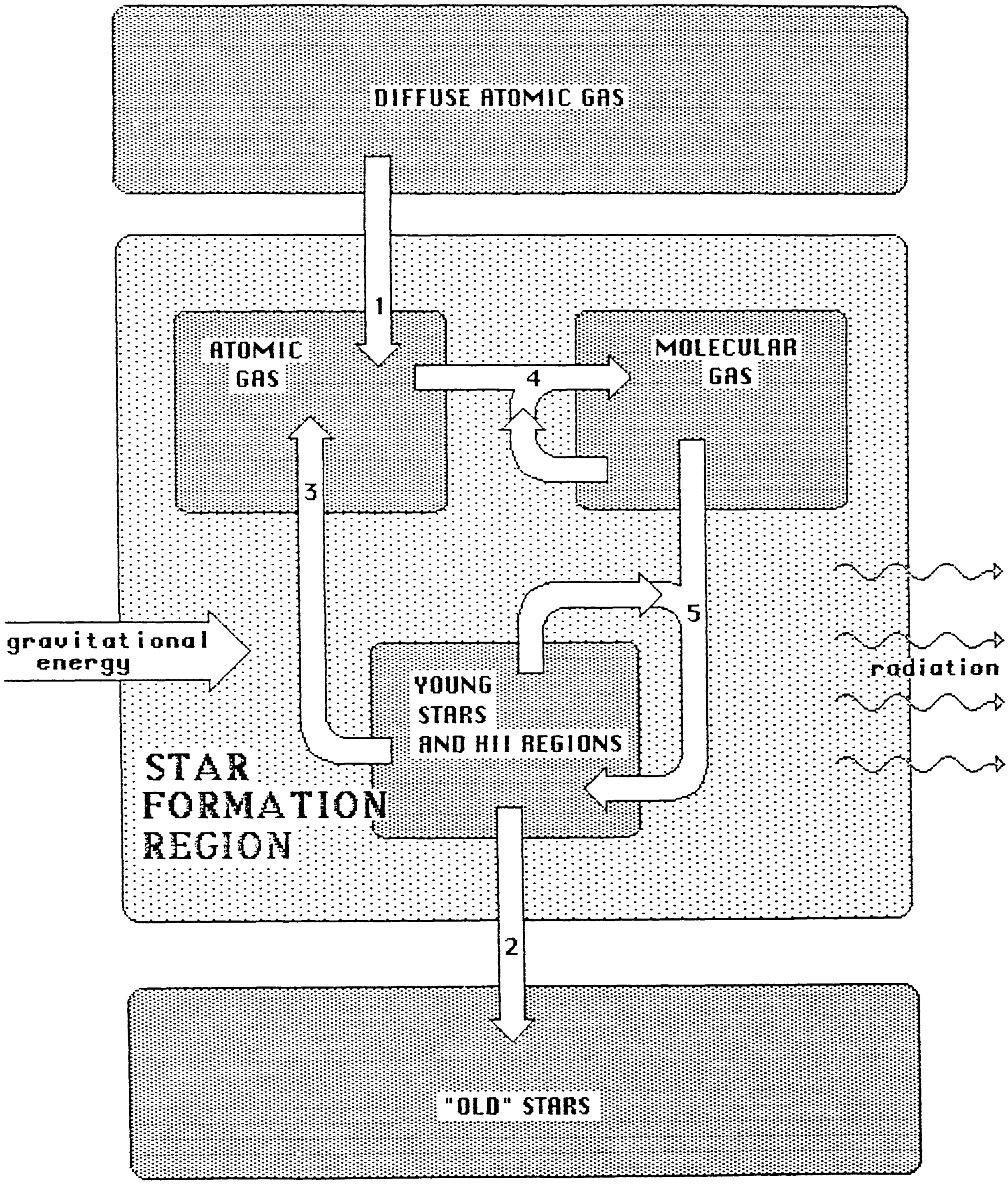

Fig. 2. The process system of a star formation region amounts globally to a transformation of diffuse atomic gas (supply reservoir) into 'old' stars (waste reservoir). Within the system the following processes must be discerned (with reference to the number within the arrows): inflow of gas (1); stellar evolution (2); stellar mass loss and recombination of ionized gas (3); production of molecular gas (4); triggered star formation (5).

state is given by

$$a_0 = \frac{k_2^{1/n}(k_2^{1/n} - 1)}{k_1 + k_2^{2/n}} , \tag{6a}$$

$$m_0 = \frac{1}{k_2^{1/n}} , \tag{6b}$$

$$s_0 = \frac{k_1(k_2^{1/n} - 1)}{k^{1/n(k_1 + k_2^{2/n})}} . \tag{6c}$$

The stability of this stationary state against perturbations is not guaranteed. By a linearized normal mode analysis, it is found that the stationary state, given by Equations (6), is stable if

$$k_1 > k_2^{2/n}(n - 3 - nk_2^{1/n} + 2nk_2^{1/n}) . \tag{7}$$

Figure 3 gives a graphic presentation of this condition. For a given n, the state is stable for a k_1, k_2 pair that corresponds to a point above the curve. For k_1 and k_2 values beyond

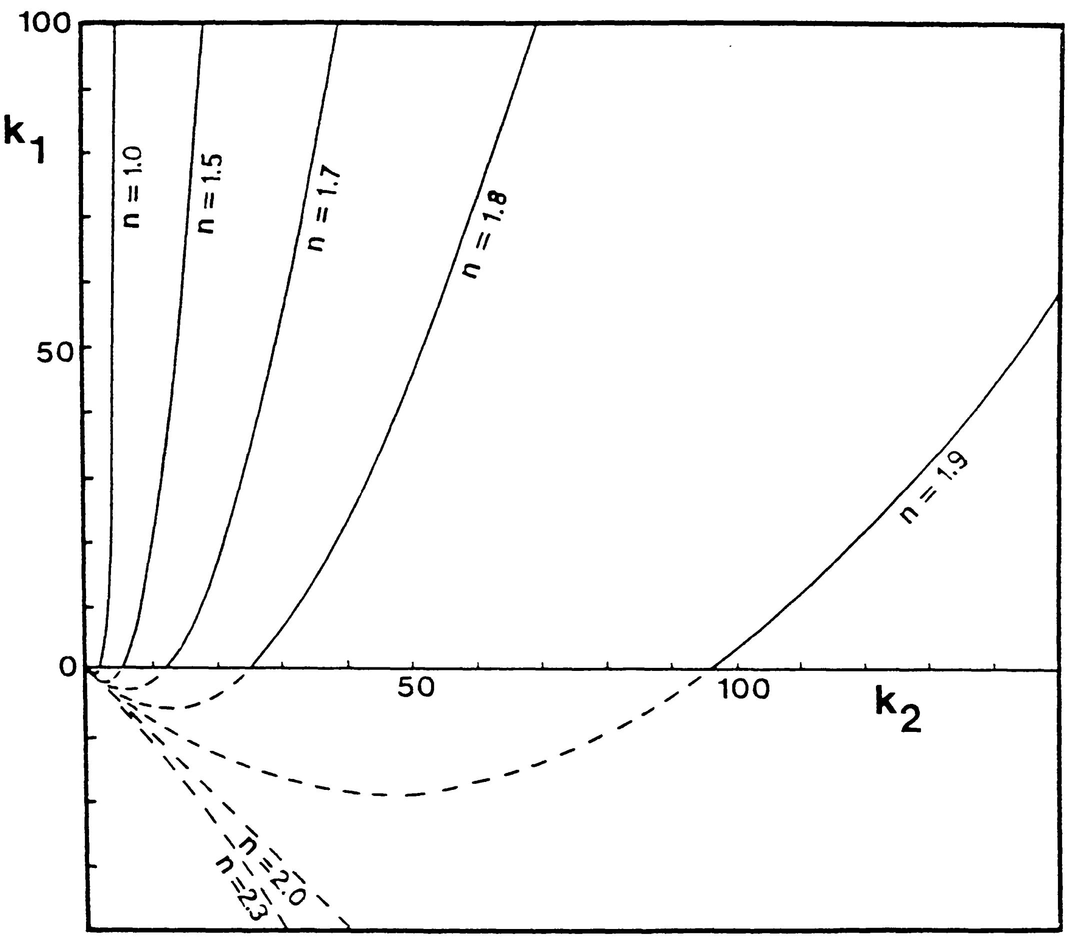

Fig. 3. Graphic representation of the stability condition of the stationary state, expressed by Equation (7). For any n, the stationary state is stable for k_1, k_2 values corresponding to a point above the curve. For points below the curve, a limit cycle occurs. For $n \geq 2$, stability is guaranteed for any k_1, k_2 pair.

the domain of stability, the solution of Equations (5) bifurcates and a limit cycle oscillation between both branches develops. The oscillations are maintained, then, by the intrinsic dynamics of the process system; no external periodic driving force is needed. Repetitive violent bursts of star formation, separated by long quiescent periods, are produced for various parameter values, especially under conditions of efficient triggered star formation.

Examples of stable stationary and regularly oscillating star formation rates in a slightly more complicated process system were shown by Bodifée and de Loore (1985). From the mathematical equations used in that paper, no stability criterion could be derived, but the equations were solved numerically. Ikeuchi and Tomita (1983) found analogous limit cycle oscillations in their model studies of the interstellar medium, composed of hot gas, warm gas, and cold clouds, regulated by supernova remnants.

The occurrence of regular limit cycles in these model computations is related to the fact that the number of independent variables was kept small. Real star formation process systems may involve more variables than have been included in the models. More bifurcations may then be expected, and a chaotic dynamic regime could set in. Hence, star formation, able to sustain itself over extended periods of time, could behave either in a stable stationary, a regular oscillating or irregular fluctuating way.

Nozakura and Ikeuchi (1984) added a diffusion transport term to the differential equations of their model and obtained spatial dissipative structures. They studied the pattern formation in a differentially rotating disk and showed that formation of spiral structures is possible in this way. Gerola and Seiden (1978) and Seiden and Gerola (1979) succeeded in explaining the irregular, patchy spiral structure of galaxies by their stochastic self-propagating star formation theory. There is a striking analogy between these spiral structures obtained by propagating processes in a rotating galaxy, and the origination of rotating spiral vortices in a wide range of autocatalytic chemical media (Zaikin and Zhabotinsky, 1970; Winfree, 1972, 1973). Multi-armed vortices with remarkable resemblance to the large-scale structure of a spiral galaxy, were obtained experimentally in an active chemical medium by Agladze and Krinsky (1982). However, Freedman and Madore (1984) warned for the nonuniqueness of the basic assumptions leading to spiral structures in self-propagating star formation models. They argue that *any* propagation in a shearing disk guarantees spiral structure. Hence, these model computations cannot be used to study the nature of the propagated process, whatever their merit in explaining galactic spiral structure.

6. Conclusions

Star formation regions are older than the individual nebular and stellar objects comprising them. Morphological and structural similarities between star formation regions in different environments dictate an internal origin for their behavioural and structural properties. Therefore, these systems are manifestations of a galactic self-organization regulated by a complex process system. Active feedback control, rather than relaxation towards equilibrium, lies at the origin of these galactic structures.

A star-forming system is not to be conceived as a spatially well-defined region, outlined by its boundaries, position or contents; but it should be defined as a coherent process system, with an ordered internal distribution of its contents, i.e., a dissipative structure. The processes are complex, mutually interconnected and autocatalytic, but they amount globally to the irreversible transformation of diffuse atomic gas into compact stellar remnants. The system is open and experiences a throughflow of matter and energy. This flow must not be understood as a bulk transport of matter and energy through the system but rather as a mass transformation process. It is then under the self-regulatory effect of the interacting processes that the system organized itself. In this way, a star-forming system looks like a kind of galactic 'organism': it is a functionally organized, self-sustained system, with internal processes that keep in contact with the environment, from which they are fed. Hence, the system has a 'metabolism' and an identity in the sense that it maintains its own existence as a coherent unit by its internal processes. The constituent parts are temporal, but the system is lasting, or, at least, its lifetime exceeds that of its components significantly.

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