DETERMINISTIC SELF-PROPAGATING STAR FORMATION

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Abstract

The evolution of large scale expanding structures in differentially rotating disks is studied. High column densities in some places may eventually lead to molecular cloud formation and initiate also star-formation. After some time, multi-structured arms evolve, where regions of intensive star-formation are separated from each other by regions of atomic gas or molecular clouds. This is due to the deterministic nature and to the coherence of this process. A simple model of galactic evolution is introduced and the different behaviour of Sa, Sb, and Sc galaxies is shown.

1. Introduction

Star formation in disks of spiral galaxies operates coherently on scales of a kiloparsec or more: expanding superassociations /Ambartsumian, 1947/, complexes of star-forming regions /Efremov, 1985/, coeval clusters /Lyngå and Wramdemark, 1984/ and stellar superclusters or stellar streams /Eggen, 1989, Palouš and Hauck, 1987/ were found. Clusters of HII regions and OB associations reside at separations of 1 to 4 kpc in arms of many normal spirals /Elmegreen and Elmegreen, 1983/. This superstructure of star formation in galaxies may be associated with superclouds composed of 10^6 to $4\ 10^7$ M_o of material partly in the form of molecules /Elmegreen and Elmegreen, 1987/. The fraction of molecules in superclouds decreases from 70% to 5% with increasing galactocentric distance.

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The formation of stars on such large scales could be interpreted as due to a process propagating in the galactic disk. What may be the mechanism of propagation? Groups of massive stars or OB associations release during the short lifetime of their members a large amount of energy in the form of ionising photons, stellar winds and supernovae. The total of some 10^{53} erg is injected over 10^7 years to the vicinity of an association. It pushes the ambient medium and it forms an expanding supershell. The supershells are considered in the present paper as being responsible of completing the star formation cycle (see Tenorio-Tagle and Bodenheimer 1988).

We focus on the evolution of supershells in differentially rotating disks. Molecular clouds can be formed on the tips of these elongated superstructures. They may eventually become the sites of next generation star formation. We assume that this is the mechanism of self-propagating star formation, which is deterministic in nature. Starting with the limited number of clouds, all the galaxy may be after some time populated by clouds. We also discuss a simple model of galactic evolution and show the differences between Sa, Sb, and Sc galaxies.

2. The supershells

10^{52} - 10^{54} erg released by the massive stars from an OB association in a relatively small volume in a galaxy modify over 10^7 years substantially the enviroment of the stellar cluster. An expanding supershell leaves a giant hole in the ISM. The ambient medium accumulates in the shock and the shock decelerates due to the conservation of the total amount of momentum.

The evolution of supershells was studied numerically. We use the strong shock approximation developed by Sedov /1946/, and assume that the thickness of the shock front is much smaller than the radius of the cavity. Then the completely 2D treatment of gas dynamics may be substituted by a simpler " 1.5D " approach, where the thickness of the shock is disregarded. This is sometimes also called the snow-plough model.

A more detailed description of our model may be found in our Paper I /Tenorio-Tagle, and Palouš, 1987/. The evolution of a supershell in the differentially rotating disk of a galaxy is shown in Fig. 1. The shocked, swept up matter accumulates in the shock and at the same time it slides along the front to the tips. Large column densities near the two tips result in formation of molecules as soon as the critical column density $N_{crit} = 10^{21} Z_o/Z$ cm^{-2}, required to shield

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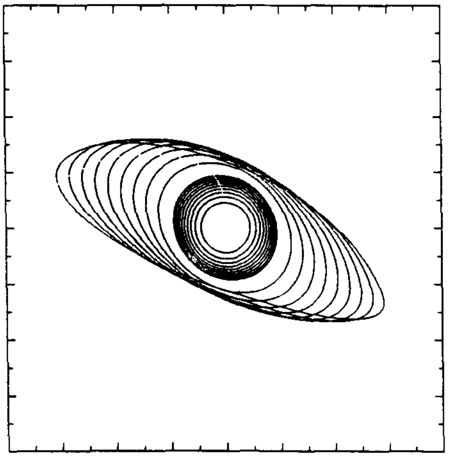

Figure 1.

Time evolution of a supershell. The first ten contours were drawn at an interval equal to 10^6 years, while for the other ones it was set equal to 10^7 years.

the external UV radiation field /Franco, and Cox, 1986/, is exceeded.

The evolution of the size, shape, inclination, density, and of the total mass have been expressed with the approximation formulas in our Paper II /Palouš, et al., 1989/. The rate of superstructure evolution, which varies from a galaxy to another, is proportional to the reference time, $t_{ref} = \pi / \alpha \kappa \; 10^9$ years, where κ is the epicyclic frequency in km s^{-1} kpc^{-1}. $\alpha = 0.74 \; \sigma_g^{0.1}$, where σ_g is the gas surface density in the galactic disk in $M_o pc^{-2}$.

In this communication we use the approximate formulas from Paper II and discuss the propagation of star formation. We assume that the lifetime of a molecular cloud is 2 to 3 10^7 years. After this time, the stars are formed in its interiors. They release over 10^7 years about 10^{53} erg disrupting the parent cloud.

3. After 500 Myr

We assume that the star formation propagates if two conditions are met:

1. the column density in the supershell is higher than the critical value $N_{crit} = 10^{21} \; Z_o/Z$ cm^{-2},
2. the total mass accumulated in the supershell is larger than the critical value M_{crit}. The propagation of star formation is connected with massive stars and we assume that they are formed in massive clouds only. We take

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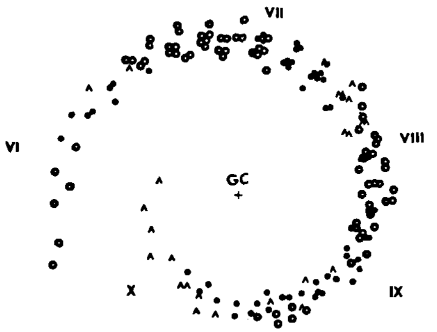

Figure 2.

The distribution of atomic /o/ and molecular clouds /●/ and OB associations /^/ after 5 10^8 years. The solid line is 32 kpc long.

$$M_{crit} \simeq 10^5 M_o .$$

Low mass clouds and clouds with low column densities, where also some star formation occurs, are, according to our assumptions, not able to propagate the star formation.

The time t_{crit} after which the column density N_{crit} is reached may be expressed from our formulas in Paper II:

$$t_{crit} = t_{ref}/f, \quad f = 1 + 0.25 \left[\frac{n_o}{1\,cm^{-3}}\right]^{0.52} \left[\frac{E_o}{10^{53}\,erg}\right]^{0.15} \left[\frac{Z}{Z_o}\right]^{0.67} , \qquad /1/$$

where n_o is the density of ambient medium and E_o is the initial energy released. The total mass accumulated in the supershell is for $t > 0.25$ t_{ref}

$$M_{tot} = 5.2 \left[\frac{h_d}{100pc}\right]^{1.5} \left[\frac{n_o}{1\ cm^{-3}}\right]^{0.54} \left[\frac{E_o}{10^{53}\,erg}\right]^{0.44} 10^5\ M_o , \qquad /2/$$

where h_d is the half-thickness of the gaseous disk. With our assumption 2 we may introduce the critical density n_{crit}

$$n_{crit} = 0.05 \left[\frac{h_d}{100pc}\right]^{-2.8} \left[\frac{E_o}{10^{53}\,erg}\right]^{0.8} . \qquad /3/$$

If the density of ambient medium n_o is less than n_{crit} the star formation do not propagate.

Let us start with one star-forming region in the galactic disk. We use the flat rotation curve with $\Theta = 220$ km s^{-1} representing Sb galaxies /Rubin et al., 1985/. We also introduced the gradients of ambient medium density, metalicity, and disk thickness: n_o and Z are larger and h_d smaller inside the diks than outside.

After 5 10^8 years /Fig.2/ several generations of clouds are created. As a consequence of shorter t_{ref}, the propagation is faster in-

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side the disk than outside. The Xth generation of clouds and stars at a small galactocentric radius evolves now when only a few generations have occurred outside /Fig.2/.

Due to the galactic differential rotation, clouds and young stellar groups form a spiral arm. It is a multistructured arm composed of several regions of 1 - 4 kpc in size, which are preferentially atomic, molecular, or star-forming. This is a consequence of the deterministic nature of propagation, and of the coherence of the process, which started from one star-forming region.

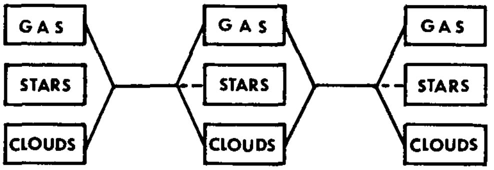
A higher fraction of gas is in the form of molecules inside rather than outside the disk. This is the result of:a. larger metalicity inside implying lower critical column density for molecule formation, and b. higher density of ambient medium inside making higher the column density in the supershell.

How galaxies differ from each other? The rate of propagation is proportional to t_{ref}, which is related to the rotation curve. Higher rotation speeds imply smaller t_{ref}. With shorter t_{ref} clouds multiply quicker, thus after certain time more rotation yields more clouds. Higher rotation yields also higher wind up of the spiral arm.

4. A simple model of galactic evolution

Starting with many randomly distributed star-forming regions, the galactic plane will be populated after some time by a huge number of clouds and hardly any spiral arm could be distinguished. In our model, the number of clouds N is a function of time. $N_{old}/t/$ randomly distributed clouds will create $N_{new}/t + \Delta t/$ clouds. The correlation in cloud positions, as described in the preceding chapter, is a consequence of limited number of clouds. For large number of clouds the correlation will be smeared out and we assume that the distribution of new clouds is a random one.

We investigate a simple model of the galactic disk evolution and express how the number of clouds change in the subsequent time-steps. The disk is represented by three components: diffuse gas, clouds and stars. Star-forming clouds are formed in the evolution of supershells from the diffuse component. But the lifetime of clouds is limited. They are disrupted as a consequence of the formation of stars in their interiors after about 3 10^7 years. The gas recycles and 90% goes back to the diffuse component. 10% does not return, it is locked up in low mass stars and in remnants after the evolution of high mass stars. The



total mass in all three components is, in this simple model, kept constant.

Our model introduce a time-delay: the old ambient gas density and the old number of clouds influence the new number of clouds and the new ambient gas density. This feedback is highly nonlinear, which is inherently connected with the deterministic nature of our model of self-propagating star formation.

The evolution starts with all mass in the diffuse gas, but few initial star-forming clouds. In early phases the number of clouds grows rapidly. This is connected with high density of the diffuse component. If the number of clouds is related to the star formation rate, the initial burst of cloud formation is followed by a burst of star formation. Subsequent decrease of n_o reduces the number of clouds. Finally, after some time, when the number of clouds is reduced to a few thousands, the evolution is very slow at almost constant density of the diffuse component of gas. t_{crit} is short in rapidly rotating Sa galaxies. This results in the steeper increase of N causing stronger burst of star formation and larger gas exhaustion in Sa than in Sc galaxies.

The above model of galactic evolution can be generalized, the halo-disk interaction introduced, as well as the chemical evolution, etc. Coalescence of small clouds, or large-scale gravitational instabilities are also relevant for star formation in galaxies. They cooperate with our mechanism of cloud formation. Evolution of galaxies results from several processes. In our opinion, the deterministic self-propagating star formation contributes to a more complex scenario.

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