WAVES OF INDUCED STAR FORMATION IN GALAXIES

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Abstract. The paper presents an analytical theory for propagation of induced star formation. The model takes into consideration a nonlocal influence in the interactions of gas clouds and stellar systems and time-delay processes in formation of new stars in clouds which have experienced the influence of previous generations of stars. The analytical solutions for propagating waves of star formation are obtained. Numerical simulations of basic equations demonstrate the formation of stationary waves and confirm the analytical results.

In two-dimensional case the formation of circular propagating waves of star formation is demonstrated. These structures can be associated with observed rings of enhanced star formation (Appleton and Struck-Marcel, 1987).

1. Introduction

The idea that the star formation possesses in some cases the properties of a self-propagating wave is by no means new. Blaauw (1964) has shown that subgroups in OB-associations are spatially ordered in chains, and the age of subgroups changes gradually from one end of chain to the other. Later, many evidences of propagating star formation in star-forming regions were obtained both in our Galaxy and in extragalactic systems. The brilliant example of the phenomenon of propagating star formation is the LMC4 region in Large Magellanic Cloud (Dopita et al., 1985). Almost a circular wave of star formation is observed in this region. The wave propagates outwards with the velocity of about 36 km s\(^{-1}\). Possible examples of a self-propagating star formation on a much larger scale are represented by galactic ring structures with the enhanced rate of star formation, described by Appleton and Struck-Marcell (1987). Although the authors themselves explain the nature of these structures as circular density waves caused by close galactic encounters, it seems more natural to connect this rings with waves of star formation, propagating in galactic discs, rich in gas.

The possibility of propagation of star formation waves is intrinsically connected with the induced character of star formation, i.e., with the ability of already existing stars to stimulate in some cases further star formation in nearby regions. Several mechanisms of this kind have been proposed. Öpik (1953) suggested that sequential star formation may occur in an expanding and fragmentating shell, created by supernova event. In recent years the possibility of the trigger role of supernovae was strongly supported in numerical simulations by Woodward (1976) and Krebs and Hillebrandt (1983). The influence of supernova explosions on interstellar matter is not the only mechanism of induced star formation. Other mechanisms are connected with the trigger role of ionisation fronts of H\(_{II}\) regions around OB-stars (Elmegreen and Lada, 1977) and stellar winds (Elmegreen and Elmegreen, 1978; Cameron, 1984).
The induced star formation is analogous to the process of autocatalysis in chemical reactions and ecology. However, the mathematical description of the induced star formation may differ from those of chemical and ecological models. Indeed the propagation of chemical waves is caused by diffusion of components in the reactor, so the general formalism for description of these processes is the reaction-diffusion type equations (Haken, 1978). Massive rapidly-evolving stars which induce further star formation do not deviate far from their birth places. Therefore, the diffusion processes do not seem to be very important for propagation of star formation. The propagation of star creation looks like a fire in the forest when surrounding trees catch fire from one burning tree at a time. Accordingly, the propagation of star formation occurs due to nonlocal influence of star or stellar clusters on interstellar medium. Another fundamental characteristic of the induced star formation which determines, for example, the velocity of the process is the delay time. It is the period between the moment the cloud experiences the influence of nearby stars, and the moment the star birth.

Seiden and Gerola (1979) or Seiden et al. (1982) based their numerical simulations on related ideas. We present here an analytical description of such nonlocal process of self-propagating star formation with time delay. As it is shown in Section 2 the reaction-diffusion type equations follow from general equations as certain limit case. Another consequence of proposed equations is an instability of star-cloud system and an increase of stellar density perturbations if cloud density exceeds a certain critical value. The numerical integration of basic equations demonstrates the evolution of an unstable stellar perturbation into a stationary wave of star formation. Two-dimensional calculations of Section 7 illustrate the development of an arbitrary perturbation into a circular propagating wave.

2. Basic Equations

We shall describe the propagation of star formation in an interstellar medium consisting of gaseous inhomogeneities or cloudlets which are the constructing material for future stars. Clouds give birth to stars with some efficiency if they have been compressed by shock fronts caused by nearby stars of previous generations. New stars born after some time of delay. The delay time depends on many factors such as the density of clouds, the cooling function, the intensity of shock fronts, etc., but we shall describe this process phenomenologically introducing the parameter of the delay T. Let C(x, t) and S(x, t) be mass densities of clouds and massive stars, respectively. If we take into account the fact that stars can induce further star formation only in their neighbourhoods, we may write the rate of star formation due to induced processes as

\[ aC(x, t - T) \int dx' S(x', t - T)f(x - x'), \tag{1} \]

where \( f(x - x') \geq 0 \) is an 'influence function' which equals zero for \(|x - x'| > L\). This function describes the nonlocal process of the induced star formation, so L is an effective radius of sphere, inside of which a star may induce the star formation in neighbouring