Star Formation and Evolution of Galaxies

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Abstract. We discuss how the star formation influences the evolution of galaxies. Processes in the ISM combine the gravitational instability with hydrodynamical instabilities triggering formation of stars. Various feedback processes operating in the star forming regions such as stellar winds, ionising radiation, and supernova explosions produce bubbles of hot gas containing yields of the stel lar evolution surrounded by expanding shells composed of the pristine material of the original molecular cloud. We discuss the hydrodynamics of winds of massive star clusters. We propose a bimodal solution, where the thermally unstable region may be the place of secondary star formation. The possibility of super winds blowing to large distances from parent galaxies is also mentioned.

Keywords: Star formation, Galactic winds and fountains, Interstellar medium (ISM) and nebulae in Milky Way, Interstellar medium (ISM) and nebulae in external galaxies
PACS: 97.10.Bt, 98.35.Nq, 98.38.-j, 98.58.-w

ISM: STRUCTURES

Interstellar medium (ISM) in galaxies is composed of several coexisting phases: molecular clouds with high density cold cores consisting of H_2, CO, and other molecules, interstellar worm medium composed mostly of neutral or ionised hydrogen, and hot medium of fully ionised plasma at temperatures larger than 10^6 K produced by explosive events like supernovae. HI in the Milky Way, and in nearby galaxies including LMC, SMC, M31, M33, HoI, HoII, IC 2573 and others, shows shells and holes. They are footprints of recent star forming events. These ISM structures up to 1 kpc in radius expand with velocities 10 - 50 km/s. A recent work [2] discovered more that 600 shells in the Milky Way.

The ISM is turbulent and dissipative: energy is dissipated in supersonic shocks between the turbulent elements and/or in collisions of interstellar clouds. Energy dissipation, which agitates the large scale instabilities in the self gravitating galactic disks, is compensated with the energy inserted by young stars, on small scale, by local gravitational instabilities, on intermediate scale, or with energy derived from galaxy rotation or galaxy versus galaxy collisions, on large scale.

STAR FORMATION

Stars form in cold dense cores of the ISM clouds. This is seen in near-by examples such as Orion molecular cloud, or Carina nebula. There, in Carina, many interesting features can be seen: dark globules and dust pillars containing the places of star formation, the massive young star η Carinae returning mass and energy into the ambient medium, a young stellar cluster Trumpler 14, and Herbig - Haro objects, signatures of the feedback from young stars.

Formation of stars in diffuse ISM clouds is a process which increases the original density of the parental cloud by some 20 orders of magnitude. It is a complex interaction between the gravitational instability, hydrodynamics of the collapse, cooling and radiative transfer inside the collapsing cloud. An open question is, if the star formation is a spontaneous process, or if it is triggered by an external action.

Collapse of a core

We would like to mention two models of the star formation, the first one is described in [14]: a dense slowly rotating core starts to collapse when the magnetic part of its support decreases due to ambipolar diffusion. The instability proceeds from “inside-out” forming the protostar surrounded with a disk embedded within an infalling envelope of dust and gas. At this stage, the radiation is produced by accretion shocks, when the material falls onto the central protostar and disk. The temperature in the central region starts to grow, leading to the ignition of hydrogen burning. The star becomes almost completely connective forming a stellar wind. In the plane of the protostellar disk, the wind is blocked, but the mass infall towards the disk continues. The outflow wins in the direction perpendicular to the disk producing bipolar collimated jets. The bow shocks, resulting from their interaction with the ambient molecular cloud, are seen as Herbig - Haro objects.

A turbulent cloud

The second model is introduced in [8], [5], and [13]. It invokes the supersonic collisions of turbulent eddies and filaments creating the dense star formation places. Supersonic turbulence shows a complex network of interacting shocks, establishing converging flows. In their focuses, the high density regions are formed, which may become gravitationally unstable. The gravitational collapses detach them from the turbulent medium, if they are sufficiently fast. The gravitational instability leading to star formation has to develop before the next supersonic shock arrives and disrupts the high density region. Turbulent motions support the cloud against the gravitational collapse on the large scale, and at the same time they form the gravitationally unstable high density regions on small scale. When the turbulence is too strong, the subsequent supersonic shocks arrive to a dense region too frequently quenching the star formation. On the other hand, when the turbulence is weak, the self-gravity completely overwhelms the turbulent support, turning the region into a star burst.

The Feedback of the Star Formation

As soon as the young stars are created, they provide the energy and mass into the ambient ISM. The stellar radiation forms expanding HII regions, the stellar winds caring the nuclear burning products form bubbles and galactic fountains. Supernova explosions contribute to the stellar feedback with energy and metals. The stellar feedback drives the supersonic turbulence in the ISM, which would otherwise die out. A quasi-equilibrium between the stellar feedback and turbulence is established: more star formation produce stronger feedback increasing the level of turbulence, which results in the decrease of star formation and less feedback decreasing the level of turbulence.

The Triggered Star Formation

There are various scenarios of triggered star formation, we mention here only one, connected to the momentum and energy feedback in star forming region. The shock front at the leading edge of expanding bubbles collects the mass from the ambient medium. When its density increases the cooling sets in forming a thin and cold expanding shell. The shell may become gravitationally unstable, fragment, and create the places of secondary star formation. This “collect and collapse” scenario is proposed in [4] and further elaborated in [3] and [18]. Its reality as a triggered star formation mechanism it has to be checked with observations and tested in future simulations.

Galactic Fountains

The mass and momentum feedback of young and massive stars of OB associations forms expanding bubbles surrounded with shells. Their expansion in the direction perpendicular to the galactic disk, in the direction of decreasing density of the ISM, leads to acceleration of the expansion velocity and to the blow out from the galactic disk. Due to Rayleigh-Taylor instability, the shell breaks into fragments forming a galactic fountain. The hot and metal enriched material of the bubble flows to the galactic halo, where it stays until it cools down and rains back in the form of metallic droplets [16]. The fragmented shell moves in the gravitational potential of the galaxy arriving back to the disk up to a few kpc away from the formation place of the original OB association [15]. Thus the galactic fountains serve as an effective mixing mechanism of the ISM in the rotating galactic discs.

A Global Law of Star Formation

Measurements of the H_α emission combined with HI and CO distribution in several nearby galaxies in [7] and [9] discovered the relation between the total gas surface density Σ_{HI+H_2} and star formation rate (SFR):

$$SFR = \Sigma^{1.4}_{HI+H_2}. \tag{1}$$

Besides the star formation law (1), there, in the star forming discs, there is a threshold value of the gas surface density $\Sigma_{(HI+H_2),crit}$ below which the star formation does not happen. The value of this critical surface density vary from galaxy to galaxy depending on the Toomre Q parameter:

$$Q = \frac{\sigma\kappa}{\pi G \Sigma_{HI+H_2}}, \tag{2}$$

where σ is the gas velocity dispersion, κ is the local epicyclic frequency, and G is the gravitational constant. This relation was also mentioned in [11]. Proper explanation of this observational law is discussed: star formation happening in turbulent clouds may be connected to pressure in the ISM, which depends on the total gas surface density Σ_{HI+H_2}.

EVOLUTION OF GALAXIES

The evolution of galaxies is influenced by internal and external processes. The bar formation and dissolution, the growing central mass concentration, formation of spiral arms, which combine with star formation and mass and energy feedback. The internal processes are complemented, or sometimes dominated, by external processes such as galaxy versus galaxy interactions, tides, major or minor mergers triggering bursts of star formation and formation of massive star clusters. Galaxies in clusters are subjected to high speed galaxy encounters causing the galaxy harassments events. Another process happening in galaxy clusters is the gas stripping by ram pressure due to galaxy high speed motion in the diluted and hot intra-cluster medium. A brief review of the galaxy evolution is given in [10].

MASSIVE STELLAR CLUSTERS

Young and massive stellar clusters, frequently called super star clusters, are preferentially observed in the interacting galaxies. Their stellar mass amounts to several million $M_\odot$ within a region less that a few parsecs in diameter. They represent the dominant mode of star formation in starburst galaxies. Their high stellar densities resemble those of globular clusters, where several stellar populations have been observed [12].

To explain the presence of multiple stellar generations in globular clusters, the slow wind emerging from a first generation of fast rotating massive stars, is invoked in [1]. The authors argue that the fast rotating massive stars function as a filter separating the H-burning products from later products of He-burning. However, it is not clear why all the massive stars rotate fast, and why the slow wind produced by stellar rotation is just retained inside the potential valley of the stellar cluster.

Another solution, how to form the second generation of stars in massive star clusters, is proposed in [17], [19], and [20]. We propose a bimodal solution, where in a central part of a massive star cluster forms a thermally unstable region (see Fig. 1). In this region,

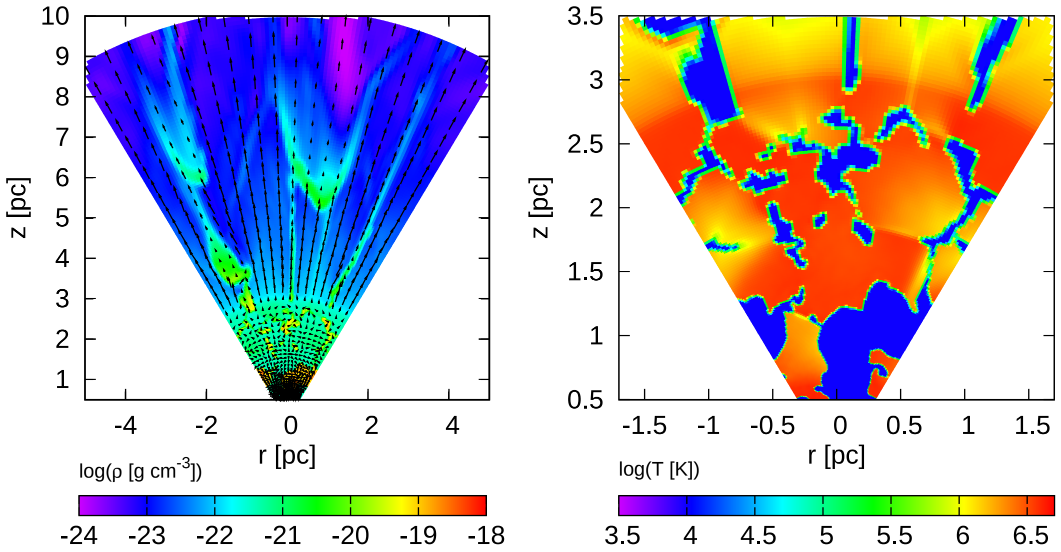

FIGURE 1. 2D hydrodynamic simulation of the Super Star Cluster wind in which radiative cooling was taken into account. The cluster has a radius 3 pc, its mass is approximately 3×10^6 $M_\odot$. In the left panel, the colour shows the logarithm of the wind density, the arrows show the wind velocity which reaches approximately 500 $\mathrm{km\,s^{-1}}$ at a larger distance from the cluster. The cluster interior is filled with the hot gas heated up by the thermalization of the mechanical energy of individual stellar winds. However, due to the wind high density and hence intensive radiative cooling, the thermal instability occurs leading to a formation of dense warm ($T \sim 10^4$ K) clumps (see the right panel which shows the logarithm of the wind temperature). A fraction of these clumps is accelerated by the surrounding hot wind and ejected from the cluster, but most of them stay in the cluster where they eventually feed next episodes of star formation.

the thermal instability creates cold regions surrounded by hot medium imploding into them. This forms broad spectral lines, which eventually may be observed [6].

The second generation of stars may be formed out of cold clumps produced by thermal instability. They are enriched by products of H-burning, increasing the effectiveness of cooling. The later He-burning products are in fast wind, which cools much less. Thus, with the thermal instability, we may separate the H-burning and He-burning products, and form the He enriched second generation of stars in clusters.

The feedback of massive stars in super star clusters create the galactic wind, or super wind, which reaches several kiloparsecs away from the parent galaxy transporting the products of stellar burning into the intergalactic space. How effective the super winds of super star clusters can be should be discussed in future. The bimodal solution, providing a possible solution for multiple populations in globular clusters, limits the super winds, thus only certain range of cluster masses is the proper candidate.

SUMMARY

We give a short and incomplete review of star formation and its influence on the evolution of galaxies. The ISM structures are discussed and confronted with star formation models including ambipolar difussion, or based on principles of a turbulent cloud. We mention the feedback from young stars, triggered star formation using the “collect and collapse” scenario, and galactic fountains. Global star formation law is also described. Finally, we discuss the massive star clusters, where the multiple stellar generations may be interpreted with bimodal winds.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support by the Institutional Research Plan AV0Z10030501 of the Academy of Sciences of the Czech Republic and by the project LC06014 Center for Theoretical Astrophysics of the Ministry of Education, Youth and Sports of the Czech Republic. RW acknowledges support by the Human Resources and Mobility Programme of the European Community under the contract MEIF-CT-2006-039802

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