Astrophys Space Sci (2009) 324: 195–198
DOI 10.1007/s10509-009-0127-2

ORIGINAL ARTICLE

The astrophysical consequences of the bimodal hydrodynamic solution of the super star cluster winds

Jan Palouš · Richard Wünsch ·
Guillermo Tenorio-Tagle · Sergio Silich

Received: 11 January 2008 / Accepted: 12 March 2008 / Published online: 15 September 2009

Abstract The mass reinserted by young stars in an emerging massive compact cluster shows a bimodal hydrodynamic behaviour. In the inner parts of the cluster, it is thermally unstable, while in its outer parts it forms an outflowing wind. The chemical homogeneity/inhomogeneity of low/high-mass clusters demonstrates the relevance of this solution to the presence of single/multiple stellar populations. We show the consequences which the thermal instability of the reinserted mass has on galactic superwinds and discuss the open issues raised by the bimodal solution of stellar winds of massive clusters.

Keywords Stars: winds · Stars: clusters · ISM: HII regions

1 The formation of clusters

The expansion of an HII region in a molecular cloud induces the formation of small stellar groups via the collect-and-collapse scenario (Elmegreen and Lada 1978). The propagation of an ionisation front in a turbulent medium drives the shell, which fragments, forming several self-gravitating objects (Dale et al. 2007; Mac Low et al. 2007). Dynamical expansion of ionisation and dissociation fronts is also computed by Hosokawa and Inutsuka (2005, 2006a, 2006b, 2007), who use hydrodynamical equations with radiative transfer. They describe the triggered star formation due to fragmentation of a molecular shell. Observations of star formation triggered at the borders of the Galactic HII regions Sh2-104, RCW 79 and RCW 120 have been reported by Deharveng et al. (2007) and Zavagno et al. (2007).

The energy inserted through stellar winds and radiation of young stars drives shells, which collect the mass of the parent molecular cloud. Thus, the chemical composition of stars formed due to shell fragmentation corresponds to the chemical composition of the original cloud. The yield from the first stars stays in the hot phase. Its mixing with the cold molecular cloud is rather ineffective: the cloud is dispersed via stellar feedback and the enriched wind with the yield blows away into the general interstellar medium (ISM).

Star clusters form by merging of smaller stellar groups formed simultaneously in a given molecular cloud. The size of a future stellar cluster depends on the efficacy of the merging process: in a massive giant molecular cloud (GMC), where many small stellar groups form, a more massive cluster may emerge compared to a low-mass molecular cloud, where only a few stellar groups form. In low-mass clouds, the groups are also less strongly gravitationally bound, which leads to more stars escaping when the merging sets in.

The chemical homogeneity of open star clusters like the Hyades (De Silva et al. 2006) and Collinder 261 (De Silva et al. 2007) proves that they were formed from a well-mixed cloud and that any stellar self-enrichment did not take place there. The case for globular clusters is quite different: the abundance patterns are attributed to self-enrichment (Brown et al. 1991). The star-to-star abundance inhomogeneities among the light elements (Bekki and Chiba 2007) imply that the self-pollution of the parent molecular cloud by stellar

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J. Palouš (✉) · R. Wünsch
Astronomical Institute, Academy of Sciences of the Czech Republic, Prague, Czech Republic
e-mail: palous@ig.cas.cz

R. Wünsch
University of Cardiff, Cardiff, UK

G. Tenorio-Tagle · S. Silich
INAOE, Puebla, Mexico

winds from massive stars of the first generation can cause the abundance inhomogeneities, when low-mass stars form from the polluted molecular cloud. The problem is how to keep the winds of the first-generation stars inside the cloud, and how to protect the cloud against disintegration.

In merging galaxies and starbursts, young, massive and compact star clusters, often called ‘super star clusters’ (SSCs), have been discovered (Whitmore et al. 1999; Zhang et al. 2001; Whitmore 2007). In the interacting pair NGC4038/39, the Antennae galaxies, there are several thousand SSCs. Their low cluster-to-cluster velocity dispersion excludes the possibility that they have been formed due to an increased rate of high-velocity cloud–cloud collisions; their preferred formation mechanism is probably due to increased ISM pressure pushing the GMCs to collapse. Their average age of $\sim 10^7$ yr, which is independent of their position relative to the galaxy collision lasting $\sim 10^8$ yr (Fall et al. 2005), leads to the conclusion regarding the high ‘infant mortality’ of the clusters: 90% of the clusters dissolve in the first 10 Myr due to momentum and energy feedback from young and massive stars removing a large fraction of the original mass of the parent cloud. Most clusters do not survive more than ~ 10 Myr. However, some of the most massive clusters survive rather long, becoming possible precursors to metal-rich analogues of globular clusters.

2 The radius versus luminosity plane

In the parameter space of cluster structural parameters including the half-mass radius, the total mass and the binding energy, globular clusters define a narrow fundamental plane (Barmby et al. 2007). This is a relationship between a cluster’s size, total mass and internal velocity dispersion. In this contribution we refer to previous papers by Tenorio-Tagle et al. (2007) and Wünsch et al. (2007), where a threshold line divides two different behaviours of mass reinserted into the cluster volume in the radius versus luminosity (or total mass) plane. The additional knowledge of the internal velocity dispersion, or binding energy of the cluster, would lead to conclusions on cluster survival. Here, we focus on the hydrodynamics of the reinserted mass.

Let us assume a uniform distribution of stars in a spherical volume of the cluster of the radius R_{sc}. Stars deposit kinetic energy and mass via stellar winds and radiation at a given rate proportional to the stellar density. This energy is thermalised in supersonic shocks between expanding fronts. We do not describe the thermalisation process in detail; we just assume a certain heating efficiency, η, which we keep between 0.1 and 1.0. This thermalisation increases the temperature inside the cluster to a high value of $\sim 10^7$ K, creating an internal overpressure driving an outflowing hot wind, which takes all the reinserted mass away. The gaseous outflows driven by massive clusters are described by hydrodynamical equations by Chevalier and Clegg (1985), who derived a solution assuming an adiabatic behaviour of the wind.

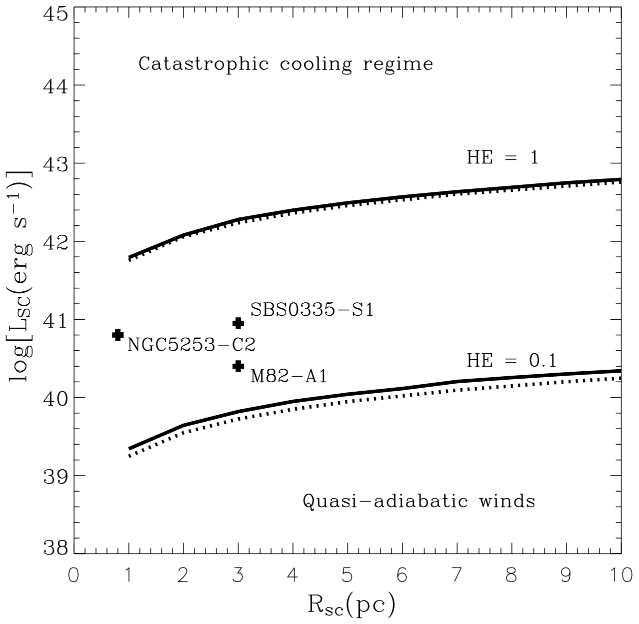

Fig. 1 The threshold line. Clusters below the threshold line produce a wind blowing away all the mass reinserted by stars. Clusters far below the threshold exhibit hot winds. Near the threshold line the wind cools down, forming compact HII regions. Above the threshold line, a fraction of mass reinserted by stars becomes thermally unstable. Warm clumps inside the cluster are places of secondary star formation

Silich et al. (2004) argue that when the cluster is sufficiently dense, the adiabatic solution for the wind does not apply any longer. In such cases, we need to adopt a more consistent radiative solution. They show that winds of massive and compact clusters cool down to a low temperature at the distance of a few cluster radii. The hot $\sim 10^7$ K wind exists only in the region adjacent to the cluster. At somewhat greater distances, where the wind temperature declines to $\sim 10^4$ K, a compact HII region forms. They also show that this radiative solution exists only for stellar densities below some threshold value: when the cluster mass at a given radius increases beyond a given value, no self-consistent radiative solution including the full cluster volume and the wind exists.

The solution above the threshold luminosity (or mass) for a given cluster radius was proposed by Tenorio-Tagle et al. (2007) and Wünsch et al. (2007). The wind forms inside the cluster only beyond a certain distance from the cluster centre R_{st} (stagnation radius), taking away all of the mass reinserted beyond R_{st}. The region inside the stagnation radius is thermally unstable. There, the reinserted mass forms warm clumps, which may eventually produce cold cores, if they are large enough to shield themselves from the ionising radiation. These cold cores may be the sites of secondary star formation. At the same time, the region of the hot wind outside the cluster becomes even smaller. Already close to the cluster, the wind is warm, possibly forming an ultra-compact H II region.

In Fig. 1 we show the Rsc versus $L_{\rm sc}$ (cluster luminosity) plane, where the lines for the threshold luminosity $L_{\rm crit}$ are shown. The lines give the threshold luminosity for two values of η, 0.1 and 1.0. The analytical solution (solid line) according to Wünsch et al. (2007) nicely corresponds to the semi-analytical solution (dotted line) from Silich et al. (2007). The location of a few massive SSCs with respect to these threshold lines is indicated.

3 Astrophysical consequences

As argued by Fall et al. (2005), the increased rate of SSC formation in interacting galaxies may be due to the increased external pressure created when the ISM is compressed during galaxy–galaxy collisions. The pressure-bounded, self-gravitating GMCs are pushed to gravitational collapse when sufficiently compressed. A model of a 'star-forming factory' has been proposed by Tenorio-Tagle et al. (2003). In a collapsing turbulent cloud, small stellar groups randomly dispersed throughout the volume form first (Klessen et al. 2000). Later, they dynamically interact and merge, forming larger stellar clusters.

The existence of a thermally unstable central region in emerging clusters, which is predicted when the cluster reaches the mass above the threshold line, provides a solution for the star-by-star abundance inhomogeneities observed in massive clusters (Bekki and Chiba 2007). The second stellar generation may form from the worm clumps in the thermally unstable region of the wind. Naturally, the material of the warm clumps is enriched by the products of stellar evolution from the first generation of stars, since the yield is distributed via stellar winds. This solution does not suffer from cluster disintegration due to momentum and energy feedback: warm clumps formed from the wind inside the cluster have rather low clump-to-clump velocity dispersions. If they are places of secondary star formation, the second generation of stars stays inside the cluster. The action of the wind is only significant at the outer skin of the cluster, which means that much less mass can be removed and the emerging cluster is more stable.

Can galactic winds be driven by SSCs? The clusters close to and above the threshold in the radius versus luminosity plane produce winds that cool down close to the cluster. This natural confinement of the hot wind to a small volume near the cluster shows that ultra-compact H II regions (UCHII) may form there. However, such clusters are irrelevant to the formation of galactic winds, which need to combine the actions of winds from several star clusters. However, the conclusion as regards the cluster mortality is that 90% of the clusters dissolve within 10 Myr. This is due to the action of the hot winds. Therefore, 90% of clusters can produce galactic winds. The remaining 10% probably form UCHII and future metal-rich analogues of globular clusters.

With increasing cluster luminosity at the same cluster radius, the stagnation radius approaches the cluster radius, reducing the volume of the wind-forming region. This brings us to the question as to whether there is any maximum cluster luminosity, above which the clusters do not produce any winds. This may give another line in the radius versus luminosity plane above which no clusters exist. To check this prediction, we need a better model of the star cluster and of the mass distribution in the ambient ISM.

4 Open issues

As we can see in Fig. 1, a very important parameter is the efficiency of the conversion of the stellar wind's mechanical energy into thermal energy, η. Its value can shift the positions of many clusters close to or even above the threshold line separating the region of the bimodal behaviour of the stellar ejecta.

In fact, η can be a function of the distance from the cluster centre, $\eta(R)$, which can be a consequence of early mass segregation and of the radial dependence of the stellar density ν_*. The relaxation due to two-body interactions is much faster in small groups compared to large-N systems. Consequently, mass segregation proceeds much faster in small groups. This early mass segregation is conserved in the process of large cluster formation via the merging of smaller groups (McMillan et al. 2007). In a mass-segregated cluster with more massive stars closer to the cluster centre, the heating efficiency should differ between regions of different average stellar mass.

Another factor can be the dependence of the conversion efficiency on stellar density and chemical composition of the stars of the first generation, $\eta = \eta(\nu_*, Z)$. The cluster luminosity is also a function of time, which moves its position in the radius–luminosity plane, and changes its distance from the threshold line. Further steps in our model should include a more sophisticated treatment of the star formation in cold clumps.

This brings us to the formation of the first globular clusters in dwarf galaxies before the epoch of reionisation (Bromm and Clarke 2002) and to the formation of Populations III stars in the first protogalaxies, where the radiative feedback and early chemical enrichment pays an essential role (Johnson et al. 2007). The formation of H II regions in minihaloes of protogalaxies can be addressed this way.

Acknowledgements This study was partially supported by the Institutional Research Plan AV 10030501 of the Astronomical Institute, Academy of Sciences of the Czech Republic and the project MŠMT LC06014 Center for Theoretical Astrophysics. We also acknowledge support from Conacyt (México) grant 47534-F and grants AYA2004-08260-C30-01 and AYA 2004-02703 from the Spanish Ministerio de Educación y Ciencia. R.W. acknowledges support from the Human Resources and Mobility Programme of the European Community under the contract MEIF-CT-2006-039802.

Appendix: Discussion

Elmegreen: How much enrichment do you expect for second-generation stars in the extreme cases of highly-trapped winds and supernovae?
Palouš: If the second-generation stars form from thermally unstable clumps in the wind, their chemical composition can be up to solar or a few times solar.

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