Triggered Star Formation in a Turbulent ISM
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Super massive star clusters: from superwinds to a cooling catastrophe and the re-processing of the injected gas

S. Silich[1], G. Tenorio-Tagle[1], C. Muñoz-Tuñón[2] and J. Palouš[3]

[1] Instituto Nacional de Astrofísica Optica y Electrónica, AP 51, 72000 Puebla, México
email: silich@inaoep.mx

[2] Instituto de Astrofísica de Canarias, E 38200 La Laguna, Tenerife, Spain
cmt@ll.iac.es

[3] Astronomical Institute, Academy of Sciences of the Czech Republic, Boční II 1401, 141 31 Prague, Czech Republic
email: palous@ig.cas.cz

Abstract. Different hydrodynamic regimes for the gaseous outflows generated by multiple supernovae explosions and stellar winds occurring within compact and massive star clusters are discussed. It is shown that there exists the threshold energy that separates clusters whose outflows evolve in the quasi-adiabatic or radiative regime from those within which catastrophic cooling and a positive feedback star-forming mode sets in. The role of the surrounding ISM and the observational appearance of the star cluster winds evolving in different hydrodynamic regimes are also discussed.

Keywords. galaxies: star clusters, galaxies: starburst, ISM: jets and outflows

1. Introduction

In many starburst galaxies, in interacting and merging galaxies, a substantial fraction of star formation is concentrated in a number of compact, young and massive stellar clusters (SSCs) which may represent the earliest stages of globular cluster evolution. In the extreme scenario SSCs represent the dominant mode of star formation in these galaxies (see, for example, McCrady *et al.*, 2003; Smith *et al.*, 2006 and references therein). Powerful gaseous outflows associated with such clusters are now believed to be one of the major agents leading to a large-scale structuring of the ISM in the host galaxies and to the dispersal of heavy elements into the ISM and the IGM.

Analysis of the SSC's outflows led us to realize that radiative cooling may crucially affect the hydrodynamics of the star cluster winds and that the superwind concept proposed by Chevalier & Clegg (1985) required a substantial modification in the case of very massive and compact star clusters. We demonstrated that there exists the threshold line in the mechanical energy input rate vs the cluster size parameter space. This line separates clusters whose outflows evolve in the quasi-adiabatic or radiative regime from those in which catastrophic cooling sets in inside the cluster. In the catastrophic cooling regime (above the threshold line) at least some fraction of the matter reinserted via strong stellar winds and supernovae remains bound within the cluster and is finally re-processed into new generations of stars (see Tenorio-Tagle *et al.*, 2005; Wünsch *et al.*, 2006). Here we review the subject and discuss also how the high pressure in the surrounding medium may prohibit the development of high velocity star cluster winds turning them into low velocity, subsonic outflows. Finally, we make some predictions regarding the observational manifestations of the star cluster outflows evolving in the different hydrodynamic regimes.

2. The threshold mechanical luminosity

In the stationary regime the injection of matter by supernovae and stellar winds, $\dot{M}_{SC}$, is balanced by the mass outflow driven by the large central overpressure which results from the efficient thermalization of the kinetic energy, L_{SC}, deposited by SNe and stellar winds:

$$\dot{M}_{SC} = 4\pi R_{SC}^2 \rho_{SC} a_{SC}, \tag{2.1}$$

where R_{SC} is the radius of the cluster, ρ_{SC} is the density of the out-flowing gas at the star cluster surface, and $a_{SC} \approx V_{A\infty}/2$ is the speed of sound at the star cluster edge. $V_{A\infty} = (2L_{SC}/\dot{M}_{SC})^{1/2}$ is the adiabatic wind terminal speed. Equation 2.1 indicates that the density of the plasma inside more massive clusters is larger, if other parameters $(R_{SC}, V_{A\infty})$ do not change. This implies that the impact of radiative cooling on the star cluster winds becomes progressively more important for more massive clusters.

Silich *et al.*, 2004 and Tenorio-Tagle *et al.*, 2005 have demonstrated that for larger or more massive clusters, the larger the leakage of thermal energy. This leads first to a sharp drop in the wind temperature at some distance from the star cluster surface. When the mechanical energy input rate, L_{SC}, exceeds the critical value, the stationary wind solution is inhibited. The critical power is defined by the condition that the central pressure reaches the maximum value allowed by the radiative cooling. The critical energy crucially depends on the thermalization or heating efficiency, e_t. This parameter characterizes how efficient the transformation of the mechanical energy supplied by supernovae and stellar winds, into thermal energy is (Stevens & Hartwell, 2003; Melioli & Del Pino, 2004).

The threshold line calculated under assumption that $V_{A\infty} = 1500$ km s^{-1} for two cases, $e_t = 1$ and $e_t = 0.1$, together with several massive SSCs, is presented in figure 1a.

3. The impact of the external pressure

Radiative cooling puts important restrictions on the plasma parameters inside the cluster. In particular, the pressure at the stagnation point (R_{st}; the point where the expansion velocity is equal to zero; below the threshold line $R_{st} = 0$), which is the largest across the cluster,

$$P_{st} = kT_{st} q_m^{1/2} \left[\frac{V_{A\infty}^2/2 - a_{st}^2/(\gamma - 1)}{\Lambda(T_{st}, Z)} \right]^{1/2}, \tag{3.1}$$

is restricted by the shape of the cooling function, $\Lambda(T, Z)$, and the cluster's parameters, $q_m = 3\dot{M}_{SC}/4\pi R_{SC}^3$ and $V_{A\infty}$ (Silich *et al.*, 2004). Figure 1b displays P_{st} for clusters with critical mechanical luminosities as presented in figure 1a. Figures 1a and 1b allow one to calculate the pressure at the stagnation point for any cluster above the threshold line without knowing the location of the stagnation radius:

$$P_{st} = P_{thresh}(L_{SC}/L_{thresh})^{1/2}, \tag{3.2}$$

where L_{thresh} is presented in figure 1a, and P_{thresh} is the pressure at the stagnation point along the threshold line (figure 1b). If the pressure in the surrounding interstellar medium exceeds that at the stagnation point, $P_{ISM} \geqslant P_{st}$, the cluster is not able to blow away the inserted matter and drive a high velocity outflow. Such clusters instead of driving a high

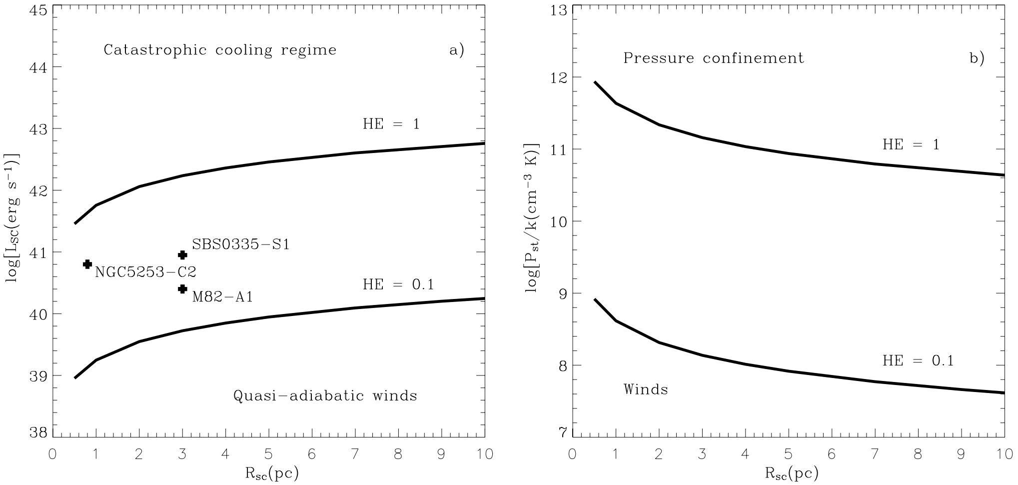

Figure 1. The threshold line. Panel a) presents the critical energy input rates for clusters with different radii. Below the threshold line the stagnation point accommodates at the star cluster center and all mass supplied by massive stars conforms a star cluster wind. Above the threshold line the stagnation point moves to some distance away from the star cluster center (see Wünsch *et al.*, 2006) and only a fraction of the deposited mass and energy leave the cluster. The calculations were done for two values of the heating efficiency, $e_t = 1$ (the upper line), and $e_t = 0.1$ (the lower line). Panel b) presents the pressure at the stagnation point for clusters with critical energy input rates, P_{thresh}. The upper line was calculated for $e_t = 1$ and the lower one is for $e_t = 0.1$. Using these two diagrams one can obtain the pressure at the stagnation point for any cluster above the threshold line (see equation 3.2). The locations of several massive SSCs with respect to the threshold lines are indicated in panel a) by the cross symbols.

velocity wind remain buried by the high pressure surrounding medium and effectively reprocess all infalling and reinserted mass into stars. Thus the high pressure ISM may prevent negative feedback and lead to a high star formation efficiency.

4. Observational appearance of SSC's winds

The efficient thermalization of the kinetic energy deposited by stellar winds and supernovae explosions results in a high temperature of the plasma within the cluster. The distributions of density and temperature inside the high velocity outflow defines then the observational manifestations of the star cluster wind in the different energy bands.

Well below the threshold line, in the quasi-adiabatic regime, the temperature rapidly reaches its asymptotic trend, $T \sim r^{-4/3}$, whereas the density drops as $\rho \sim r^{-2}$. Thus well below the threshold line star cluster winds should be associated with the diffuse X-ray sources with the hard component concentrated to the star cluster volume (see, for example, Cantó *et al.* 2000; Silich *et al.*, 2005). In the visible line regime such winds are hardly to be detected due to the fast decrease of density and the negligible emission measure at the distance where the temperature reaches $\sim 10^4$K when the outflowing plasma begins to recombine and produce an emission line spectrum.

However the temperature structure of the outflowing matter changes drastically for clusters approaching or located above the threshold line. For such clusters the temperature falls down and rapidly reaches 10^4 K at much smaller distances from the star cluster surface. This warm gas, photoionised by the star cluster Lyman continuum, moves with velocity around 1000 km s^{-1} and should be detected as a low intensity broad line emission.

When L_{SC} exceeds the threshold value, the catastrophic cooling sets in first at the center. The cooling front and the stagnation point then move from the star cluster center outwards (see Wünsch *et al.*, 2006). The temperature of the initially thermalised material then rapidly drops from $\sim 10^7$ K to approximately 10^4 K where it is balanced by the ionizing radiation from massive stars. The density of the photoionised material grows larger until the gravitational instability sets in and the accumulated gas begins to form new stars (Tenorio-Tagle *et al.*, 2005). The emission line spectra from such clusters should present the central narrow peak associated with the dense gas inside the star forming region which is located inside the stagnation radius, R_{st}, and the lower intensity broad component associated with the warm, photoionised, fast outflow. The two regions are separated by a shell of the hot, thermalised plasma which should be detected as 1.0 – 4.0 keV X-ray emission.

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Discussion

S. DIB: Can you please comment on the role of metallicity on your models – for example if the metallicity is subsolar?

S. SILICH: The cooling rate is larger in a plasma with higher metal abundance. Thus the enhanced metallicity will shift the threshold energy towards lower values and vice versa. Note however that we are dealing with matter returned to the ISM through winds and supernovae and thus we expect the metallicities to be large.

HANASZ: Do you observe the thermal instability in your system?

SILICH: We are not able to address this question in the semi-analytical approach. However, it is done in 1D full hydrodynamical calculations (see poster S237-244 by Wünch *et al.*).