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Superstellar clusters and supergalactic winds

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Abstract

We review the properties of young superstellar clusters and the impact that their evolution has in their host galaxies. In particular we look at the development of strong isotropic winds emanating from massive clusters, capable of disrupting the remains of the parental cloud as well as causing the large-scale restructuring of the surrounding ISM. As an extreme example, we infer from the observations of M82 the detailed inner structure of supergalactic winds and define through numerical simulations the ingredients required to match such structures.

Keywords: Galaxies; ISM; Starburst; Bubbles; Abundances

Contents

1. The properties of superstellar clusters

The discovery by HST of a large population of unusually compact young stellar clusters (SSCs) within starburst galaxies (see review by Ho, 1997; Johnson et al., 2001; Colina et al., 2002; Larsen and Richtler, 2000; Kobulnicky and Johnson, 1999 and the proceedings edited by Lamers et al., 2004), has led us to infer the new unit of massive or violent star formation. SSCs with masses in the range of a few $\times 10^5 M_\odot$ to up to $6 \times 10^7 M_\odot$ (see Walcher et al., 2005; Pasquali et al., 2004) within a small volume of radius 3 to 10 pc, are indeed some of the most energetic entities found now in a large variety of galaxies. Note also that collections of them have now been found within a single starburst galaxy, as in M82 and the antennae galaxy (see Melo et al., 2005; Whitmore et al., 1999).

The potential impact that these new units of star formation may have on the ISM of their host galaxies has been

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inferred from cluster synthesis models (see e.g. Leitherer et al., 1999). A coeval cluster with $10^6 M_\odot$ in stars, an initial mass function (IMF) similar to that proposed by Salpeter and an upper and lower mass range for the coeval event between 100 $M_\odot$ and $1 M_\odot$, leads initially to several tens and thousands of O stars. These however begin to disappear rather quickly (after $t \sim 3$ Myr) as they complete their evolution and explode as supernovae (SNe). The evolution of massive stars is so rapid that after 10 Myr there are no O stars left within the cluster. All massive stars undergo strong stellar winds and all of them with a mass larger than $8 M_\odot$ will end their evolution exploding as supernova. Thus, one is to expect from our hypothetical cluster several tens of thousands of SNe over a time span of some 40 Myr. During the supernova phase a $10^6 M_\odot$ stellar cluster will produce an almost constant energy input rate of the order of 10^{40} erg s^{-1}. On the other hand, the ionizing luminosity emanating from the cluster would reach a constant value of 10^{53} photons s^{-1} during the first 3.5 Myr of evolution to then drastically drop (as t^{-5}) as the most massive members of the association explode as supernova. The rapid drop in the ionizing photon flux implies that after 10 Myr of evolution, the UV photon output would have fallen by more than two orders of magnitude from its initial value and the HII region that they may have originally produced would have drastically reduced its dimensions and in fact the expectations are to have the ionization front trapped within the shell of swept up matter generated by the mechanical energy of the SSC. Thus the HII region lifetime is restricted to the first 10 Myr of the evolution and is much shorter than the supernova phase. It is important to realize that only 30% of the stellar mass goes into stars with a mass larger than $10 M_\odot$, however, it is this 30% the one that causes all the energetics from the starburst. Being massive, although smaller in number, massive stars also reinsert into the ISM, through their winds and SN explosions, almost 40% of the starburst total original mass. And thus from a starburst with an initial mass of $10^6 M_\odot$ one has to expect a total of almost $4 \times 10^5 M_\odot$ violently injected back into the ISM, during the 4×10^7 years that the SN phase lasts. From these, almost $40000 M_\odot$ will be in oxygen ions and less than $1000 M_\odot$ in iron (see Silich et al., 2001).

One of the features of the stellar synthesis models regarding the energetics of coeval star clusters is that they fortunately scale linearly with the mass of the starburst. It is therefore simple to derive the properties of starbursts of different masses, for as long as they present the IMF, metallicity and stars in the same mass range considered by the models.

When dealing with the outflows generated by star clusters, another important intrinsic property is the metallicity of their ejected matter. This is a strongly varying function of time, bound by the yields from massive stars and their evolution time. Thus, once the cluster IMF and the stellar mass limits are defined, the resultant metallicity of the ejected material is an invariant curve, independent of the cluster mass. Here we consider coeval clusters with a Salpeter IMF, and stars between $100 M_\odot$ and $1 M_\odot$, as well as the evolutionary tracks with rotation of Meynet and Maeder (2002) and an instantaneous mixing of the recently processed metals with the stellar envelopes of the progenitors (see Silich et al., 2001 and Tenorio-Tagle et al., 2003, for an explicit description of the calculations). This leads to metallicity values (using oxygen as tracer) that rapidly reach $14 Z_\odot$, and although steadily decaying afterwards, the metallicity remains above solar values for a good deal of the evolution (for more than 20 Myr), to then fall to the original metallicity of the parental cloud, once the oxygen yield has been delivered.

2. Negative feedback and the physics of supergalactic winds

The close spacing between sources within a super-star cluster warrants a very efficient thermalization of all their winds and supernova explosions, leading to the high central overpressure that is to drive both a superbubble and in some cases a supergalactic wind (SGW). The supersonic stream leads immediately to a leading shock able to heat, accelerate and sweep all the overtaken material into a fast expanding shell. In this way, as the whole structure grows, the density, temperature and thermal pressure of the wind drops as r^{-2}, $r^{-4/3}$ and $r^{-10/3}$, respectively (see Chevalier and Clegg, 1985, hereafter CC85).

Note however that such a flow is exposed to the appearance of reverse shocks whenever it meets an obstacle cloud or when its thermal pressure becomes lower than that of the surrounding gas, as it is the case in strongly radiative winds and within superbubbles. There, the high pressure acquired by the swept up ISM becomes larger than that of the freely expanding ejecta (the free wind region; FWR), where ρ, T and P are rapidly falling. The situation leads to the development of a reverse shock and with it to the thermalization of the wind kinetic energy, reducing the size of the free-wind region. Thus for the FWR to extend up to large distances away from the host galaxy, the shocks would have had to evolve and displace all the ISM, leading to a free path into the intergalactic medium through which the free wind may flow as a supergalactic wind. The energy required to achieve such a task, depends strongly on the ISM density distribution. As shown by Silich and Tenorio-Tagle (2001) the energy required to burst into the inter-galactic medium out of a fast rotating flattened galaxy is orders of magnitude smaller than that required to exceed the dimensions of a slow rotating and more spherical density distribution (see Fig. 1) with the same mass.

Given their large UV photon output and mechanical energy input rate, SSCs are now believed to be the most powerful negative feedback agents in starburst galaxies, leading not only to a large-scale structuring of the ISM and to limit star formation, but also to be the agents capable of establishing as in M82 a supergalactic wind, thereby removing processed material from galaxies and causing the contamination of the IGM (Tenorio-Tagle et al., 2003).

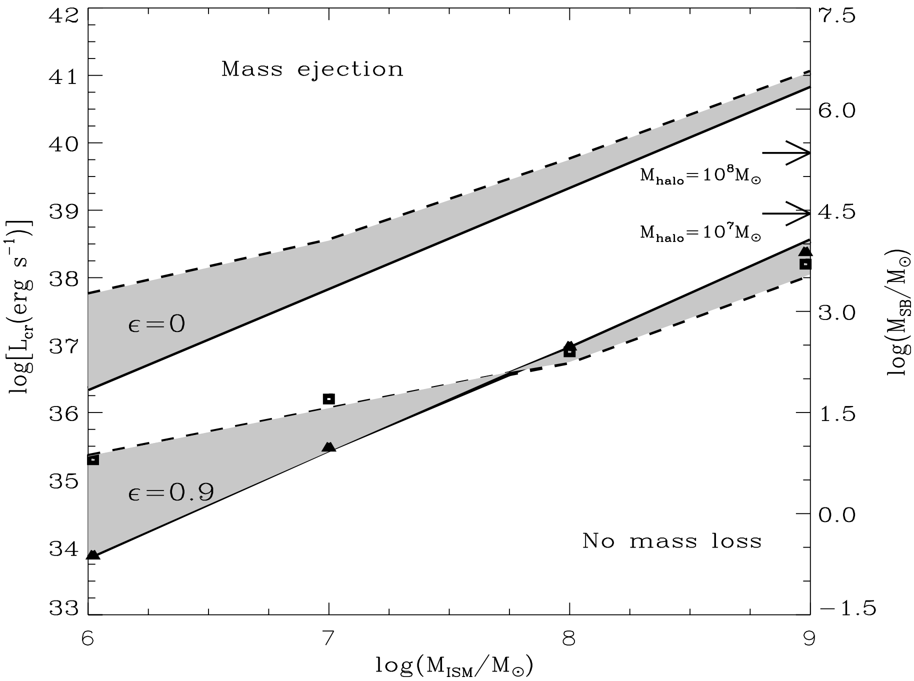

Fig. 1. Energy estimates. The log of the critical mechanical luminosity, and of the starburst mass (right-hand axis), required to eject matter from galaxies with a $M_{\rm ISM}$ in the range 10^6–$10^9 M_\odot$. The lower limit estimates are shown for galaxies with extreme values of rotation (typical of spirals) and for two values of the intergalactic pressure $P_{\rm IGM}/k = 1\ {\rm cm}^{-3}$ K (solid lines) and $P_{\rm IGM}/k = 100\ {\rm cm}^{-3}$ K (dashed lines). The upper limit estimates are for galaxies without rotation and thus presenting an almost spherical mass distribution. The resolution of our numerical search is $\Delta \log L_{\rm cr} = 0.1$. Each line should be considered separately as they divide the parameter space into two distinct regions: a region of no mass loss (below the line) and a region in which blowout and mass ejection occurs (above the line). Also indicated on the right-hand axis are the energy input rates required for a remnant to reach the outer boundary of a halo with mass $10^8 M_\odot$ and one with mass $10^7 M_\odot$, for the case of a gravitational potential provided by $M_{\rm DM} = 9.1 \times 10^9 M_\odot$ that can hold an $M_{\rm ISM} = 10^9 M_\odot$. The filled squares and triangles represent analytical energy input rate estimates.

2.1. The inner structure of M82

The biconical outflow of M82, the nearest example of a supergalactic wind (SGW), displays a collection of kpc long optical filaments embedded into an even more extended pool of soft X-ray emission. The outflow is known to extend even further, reaching the "H_α cap" at 11 kpc from the nucleus of M82 (see Devine and Bally, 1999). Both features have been partly explained either with the results of Chevalier and Clegg (1985) model of an adiabatic, freely expanding, stationary wind and/or by the remnant of a large-scale superbubble evolving into the ISM and the halo of the galaxy (see for example Suchkov et al., 1994). Both explanations, based on the energetics of a single stellar cluster, fail to explain the detailed inner structure of the outflow. The elongated filaments for example, are now known to emanate from the central starburst and are not the result of a limb brightened superbubble outer structure (Ohyama et al., 2002; Smith et al., 2006). Note also that the filaments cannot be reconciled with instabilities in the large-scale supershell, driven by matter entrainment, which occurs at large distances, kpc from the energy source. Furthermore, the stationary superwind solution leads to a laminar flow and not to gas condensation or to a filamentary structure at all. Also, as shown by Strickland and Stevens (2000) such a model fails to matched the X-ray luminosity of the M82 superwind. Note also that the adiabatic assumption, central in the model of Chevalier and Clegg, has recently been shown to be inapplicable in the case of massive and concentrated starbursts (Silich et al., 2003, 2004). Another important issue not accounted by most of the numerical simulations is the size of the waist of the biconical structure (150 pc radius in the case of M82), which in all calculated cases under the assumption of a single source of energy, (perhaps with the only exception of Tenorio-Tagle and Muñoz-Tuñón, 1997, 1998, which account for the infall of matter into the central starburst), also end up with a remnant that presents a wide open waist along the galaxy plane (see figures in Tomisaka and Ikeuchi, 1988; Suchkov et al., 1994). Further arguments regarding the disagreement between theory and observations are given in Strickland and Stevens, 2000; Strickland et al., 1997; and in Tenorio-Tagle et al., 2003.

2.2. The physics of supergalactic winds

So far, all calculations in the literature have assumed that the energy deposition arises from a single central cluster that spans several tens of pc, the typical size of a starburst. Following however, the indisputable recent observational findings with HST, we have made the first attempt to calculate the hydrodynamics that result from the interaction of the winds from neighboring young compact clusters present in a galaxy nucleus (see Tenorio-Tagle et al., 2003). Several aspects were considered in our two dimensional approach to the problem. Among these, the metallicity of the superwind matter was shown to have a profound impact on the inner structure of supergalactic winds. Full three dimensional calculations of the interaction of multiple SSC winds are now underway.

Several two dimensional calculations using as initial condition CC85 adiabatic flows have been performed with the explicit Eulerian finite difference code described by Tenorio-Tagle and Muñoz-Tuñón (1997, 1998). This has been adapted to allow for the continuous injection of multiple winds (see below).

We have considered the winds from several identical SSCs, each with a mechanical energy deposition rate equal to 10^{40} erg s^{-1}. The energy is dumped at every time step within the central 5 pc of each of the sources following the adiabatic solution of Chevalier and Clegg (1985). The time dependent calculations do not consider thermal conductivity but do account for radiative cooling, with a cooling law (Raymond et al., 1974) scaled to the metallicity assumed for every case.

Fig. 2 presents the results for which the assumed metallicity of the winds was set equal to $10Z_{\odot}$, justified by the high metallicity outflows expected from massive bursts of star formation. The winds from the SSCs are exposed to suffer multiple interactions with neighboring winds and are also exposed to radiative cooling. For the former, the issue is the separation between neighboring sources and for the latter the local values of density, temperature and metallicity. Radiative cooling would preferably impact the more powerful and more compact sources, leading to cold ($T \sim 10^4$ K) highly supersonic streams.

Fig. 2 shows three equally powerful ($L_{SC} = 10^{40}$ erg s^{-1}) superstellar clusters sitting at 0, 60 and 90 pc from the symmetry axis. All of them with an $R_{SC} = 5$ pc, produce almost immediately isotropic outflows with a terminal velocity equal to 1000 km s^{-1}. At $t = 0$ year the three clusters are embedded in a uniform low density ($\rho = 10^{-26}$ g cm^{-3}) medium. Thus our calculations do not address the development of a superbubble, nor the phenomenon of breakout from a galaxy disk or the halo, into the IGM. The initial condition assumes that prior events have evacuated the region surrounding the superstellar clusters, and we have centered our attention on the interaction of the supersonic outflows associated to the individual SSCs.

Fig. 2 shows the development of a SGW until it reaches dimensions of one kpc, together with the final temperature structure splitted into the four temperature regimes: The regime of H recombination 10^4 K–10^5 K, followed by two regimes of soft X-ray emission 10^5 K–10^6 K, and 10^6–10^7 K and the hard X-ray emitting gas with temperatures between 10^7 and 10^8 K.

The crowding of the isocontours in the figures indicates steep gradient both in density or in temperature and velocity, and thus traces the presence of shocks and of rapid cooling zones.

The interaction of neighboring supersonic winds causes the immediate formation of their respective reverse shocks,

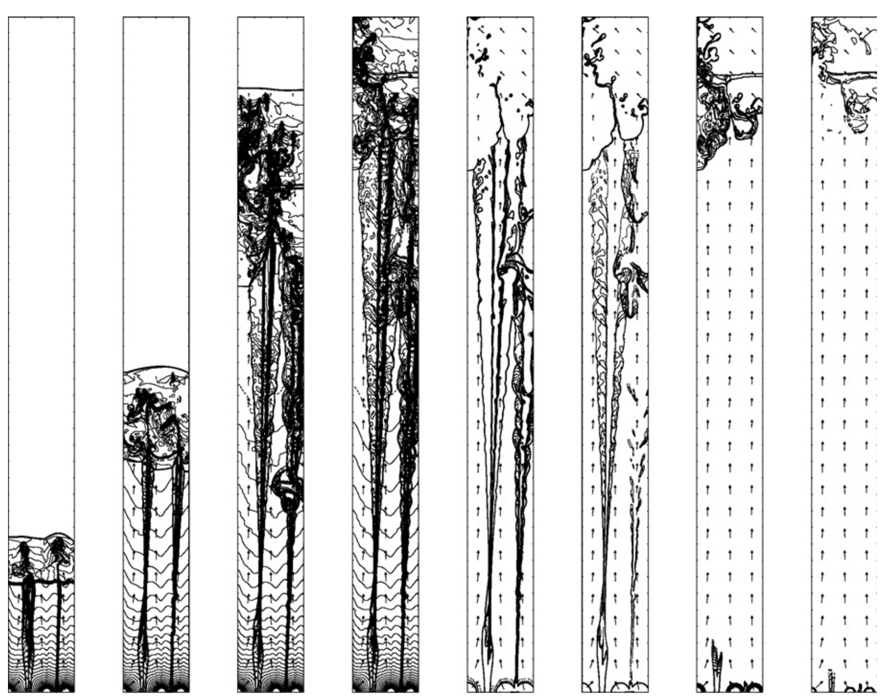

Fig. 2. Two dimensional superwinds. The first four panels represent cross-sectional cuts along the computational grid showing: isodensity contours with a separation $\Delta \log \rho = 0.1$ and the velocity field for which the longest arrow represents 10^3 km s^{-1}. The following four panels display isotemperature contours, within the range 10^4, -10^5, -10^5 -10^6, 10^6, -10^7 and 10^7 -10^8 K, respectively. Each of the superwinds has a power of 10^{41} erg s^{-1} and a radius of 5 pc. The evolution of each wind starts from the adiabatic solution of CC85. The plots displays the whole computational grid: 100 pc × 1 kpc. The assumed metallicities were $Z = 10Z_{\odot}$. The evolutionary times of the first four panels is 1.79×10^5, 4.82×10^5, 1.05×10^6 and 1.39×10^6 year, respectively.

and of a high pressure region right behind them. The pressure (and temperature) reaches its largest values at the base of the interaction plane, exactly where the reverse shocks are perpendicular to the incoming streams. The high pressure gas then streams into lower pressure regions, defining together with radiative cooling, how broad or narrow the high pressure zones, behind the reverse shocks, are going to be.

This also happens if cooling is fast enough, the oblique reverse shocks rapidly acquire a standing location. In these cases, the loss of temperature behind the shocks is compensated by gas condensation, leading to narrow, dense and cold filaments. The drastic drop in temperature occurs near the base of the outflow, where the gas density is large and radiative cooling is enhanced. The dense structures are then launched at considerable speeds ($\sim$several hundreds of km s^{-1}) from zones near the plane of the galaxy. These dense and cold structures are easy target to the UV radiation produced by the superstellar clusters and thus upon cooling and recombination are likely to become photoionized. Note however that as the free winds continue to strike upon these structures, even at large distances from their origin, the resultant cold filaments give the appearance of being enveloped by soft X-ray emitting streams.

All of these shocks are largely oblique to the incoming streams and thus lead to two major effects: (a) partial thermalization and (b) collimation of the outflow. These effects result from the fact that only the component of the original isotropic outflow velocity perpendicular to the shocks is thermalized, while the parallel component is fully transmitted and thus causes the deflection of the outflow towards the shocks. This leads both, to an efficient collimation of all winds in a general direction perpendicular to the plane of the galaxy, and to a substantial soft X-ray emission associated with the dense filamentary structure, extending up to large distances (kpc) from the plane of the galaxy. In the figures one can clearly appreciate that the oblique shocks, confronting the originally diverging flows, lead to distinct regions where the gas acquires very different temperatures, allowing for radiation in different energy bands.

From our results it is clear that a plethora of structure, both in X-rays and in the optical line regime, as in M82, may originate from the hydrodynamical interaction of neighboring winds. The interaction leads to multiple standing oblique (reverse) shocks and crossing shocks able to collimate the outflow away from the plane of the galaxy. In our two dimensional simulations, these are surfaces that become oblique to the diverging streams and thus evolve into oblique shocks that thermalize only partly the kinetic energy of the winds causing a substantial soft X-ray emission at large distances away from the galaxy plane. Surfaces that at the same time act as collimators, redirecting the winds in a direction perpendicular to the plane occupied by the collection of SSCs. Radiative cooling behind the oblique shocks leads, as soon as it sets in, to condensation of the shocked gas, and thus to the natural development of a network of filaments that forms near the base of the outflow, and streams away from the plane of the galaxy to reach kpc scales. Under many circumstances the filaments develop right at the base of the outflow and for all cases the prediction is that they are highly metallic. Hydrodynamic instabilities play also a major role on the filamentary structure. Nonlinear thin shell instabilities, as well as Kelvin Helmholtz instabilities, broaden, twist and generally shape the filaments as these stream upwards and reach kpc scales.

3. Conclusions

Superstellar clusters are the main mode of massive star formation in starburst and interacting galaxies. We have reviewed here how is that they work and the possible impact that they may have into the surrounding ISM. We have also evaluated the minimum amount of mechanical energy required to reach the outskirts of a host galaxy and shown that most sources are unable to dig the channel required for composing a supergalactic wind.

The inner structure of the super galactic wind in M82, the best known example, has been used to infer the boundary conditions required for a supergalactic wind. Calculations in the literature have left clear the fact that single energy sources lead to superbubbles and supershells evolving in the disks and the haloes of their host galaxies. However, to produce a supergalactic wind with a detailed inner structure as that of M82, a collection of compact and massive SSCs spread over the starburst radius, seems to be required.

We thus postulate that if a collection of SSCs is sitting in a preferential plane, most of the injected energy would be channeled in a direction perpendicular to the plane of the host galaxy. This is achieved naturally as a consequence of the plethora of oblique and crossing shocks that redirect the initially isotropic winds. Collimation thus occurs without the need of a thick interstellar matter disk or a torus.

Our considerations point at a new set of possible parameters that profoundly impact the development of supergalactic winds. These are:

- The number and location of superstellar clusters within a galaxy nucleus.
- The intensity of star formation, or stellar mass in every superstellar cluster, which defines their mechanical luminosity.
- The age of individual clusters, which impacts on the metallicity and thus on the cooling of the ejected matter.

All of these are relevant new parameters that may promote, as in M82, the inner structure of a supergalactic wind: the co-existense of X-rays and dense filaments, even at large distances from the sources of energy. Parameters that may promote self-collimation and with it the narrow waist of the biconical outflow. All of these features have been confirmed with full 3-D calculations, subject of a forthcoming communication. Note also that our results led to the full analysis of the HST data of M82 and to the discovery of 197 stellar clusters in the nucleus of M82 (see Melo et al., 2005).

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