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SUPERBUBBLES VS SUPER-GALACTIC WINDS

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RESUMEN

Se revisan las diferencias físicas que existen entre superburbujas y supervientos galácticos. Los dos eventos resultan de la energética producida por grandes brotes de formacíon estelar. Sin embargo los supervientos galácticos permiten el escape de los metales recién procesados por el brote estelar hacia el medio intergaláctico, mientras que las superburbujas al no llegar a alcanzar el borde de su galaxia anfitriona retienen a los nuevos metales con los que más tarde enriquecerán su medio interestelar. Se evalúan por lo mismo las principales propiedades de brotes masivos de formación estelar así como la tasa mínima de energía mecánica que un starburst ha de producir para causar la expulsión de su material recién procesado fuera de su galaxia anfitriona, tanto en el caso de galaxias con alta rotación que presenten un disco aplanado, como para el caso de galaxias con una rotación menor que imponen un límite ordenes de magnitud más energético. Se establecen los límites para galaxias con una masa de material interestelar que va de 10^6 M$_\odot$ a más de 10^9 M$_\odot$ y estos son comparados con un grupo de galaxias locales. Algunas de estas galaxias aparecen por encima del límite crítico de eyección de masa a pesar de que su estructura es la predicha teóricamente como típica de una superburbuja. Se muestra también que verdaderos supervientos galácticos, como es el caso de M82, exceden el límite crítico por más de un orden de magnitud, lo que implica que el ímite establecido por Silich & Tenorio-Tagle (2001) es una cota inferior.

ABSTRACT

Here we stress some of the major differences between supergalactic winds and giant superbubbles evolving into the giant low density haloes of galaxies. Both events are the result of massive bursts of star formation within the densest regions of the host galaxies. However, supergalactic winds are able to channel the metals produced by the recent burst straight into the intergalactic medium while superbubbles fail to reach the outskirts of the host galaxies and thus retain the newly processed metals and with them eventually raise the abundance of their ISM. We review the properties of major bursts of star formation and the critical energy (and mass of the starburst) required for mass ejection both in the case of an ISM strongly flattened by rotation into a thin disk and that imposed by a more extended ISM distribution arising from a smaller rotation. The limits are thus establish for galaxies with an ISM mass in the range 10^6 M$_\odot$ to more than 10^9 M$_\odot$, and are compared with a sample of local galaxies. Some of these galaxies seem to be above the critical limit despite the fact that their structure is clearly that of a superbubble. True supergalactic winds, as evidence by M82, are shown to exceed the critical limit by more than an order of magnitude and thus the limit derived by Silich & Tenorio-Tagle (2001) for mass ejection should be regarded as a lower limit.

Key Words: **HYDRODYNAMICS — ISM: ABUNDANCES — ISM : BUBBLES — STARS : WINDS, OUTFLOWS**

1. INTRODUCTION

The development of super-galactic winds (SGWs) is intimately related to the properties of the central massive starburst and to the distribution of interstellar matter (ISM) in the host galaxy. Clearly, to develop a SGW, through which the newly processed metals from the starburst are directly injected into the intergalactic medium (IGM), a channel, a free path, has to be carved into the ISM to finally connect the starburst with the medium surrounding the host galaxy. The process involves the propagation of shock waves into the disk and the halo of the galaxy, which lead to the formation and evolution of the so called superbubbles. These have often been mistaken with SGWs, despite their unique appearance which at all wavelengths is completely different to that presented by SGWs. Here we stress some of the main differences between SGWs and superbubbles and center our attention on three important issues: 1) The expected properties of massive burst of star formation. 2) The development of superbubbles, and 3) the physical properties of SGWs. Especial emphasis is made on the physics applicable to SGWs driven by the most massive and powerful starbursts thought to exist in the Universe.

2. THE PROPERTIES OF MASSIVE BURSTS OF STELLAR FORMATION

Our knowledge of stellar evolution has now been assembled by several groups in order to predict the properties of stellar clusters, given an IMF and a stellar mass range. These are the so called synthesis models of starbursts (Mas-Hesse and Kunth 1991, Leitherer & Heckman 1995) which predict a variety of observable quantities, as well as the energetics that one is to expect from a stellar cluster, as a function of time. Now we know that a 10^6 M$_\odot$ coeval starbursts with a Salpeter IMF and stellar masses in the range 1 - 100 M$_\odot$ leads to the appearance of several thousands of O stars strongly correlated in space (within a radius much smaller than 100 pc). 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. And therefore, one is to expect from our hypothetical cluster several tens of thousands of SN 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 10^6 M$_\odot$ cluster would reach a constant value of 10^{53} UV 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. 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 10% of the stellar mass goes into stars with a mass larger than 10 M$_\odot$, however, it is this 10% the one that causes all the energetics from the starburst. Being massive, although smaller in numbers, they also reinsert into the ISM, through their winds and SN explosions, almost 40% of the starburst 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 $\times 10^7$ years that the SN phase lasts. From these, almost 40,000 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 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.

There is a growing observational evidence pointing at massive, centrally condensed congregations of stars, as the fundamental unit of massive star formation (see Ho, 1997). These luminous structures often referred to as young globular clusters or super-star clusters, present a mass in the range of 10^5 to a few times 10^6 M$_\odot$ in stars, all pulled together within a typical radius $R_{SB} \sim 3$ pc. The brightest ones have luminosities up to two orders of magnitude higher than R136 in 30 Doradus. Similar super-star cluster properties have been inferred from HST-STIS observations of AGN (see Colina et al. 2002), and from radio continuum measurements of ultracompact HII regions not visible in optical images, fact that points to the youngest, densest and most highly obscured star formation events ever found (see Kobulnicky & Johnson 1999; Johnson et al. 2001). The massive concentrations imply a high efficiency of star formation which permits even after long evolutionary times the tight configuration that characterizes them, despite stellar evolution and its impact through photoionization, winds and supernova explosions, believed to efficiently disperse the gas left over from star formation. It is thus the self-gravity that results from the high efficiency what keeps the sources bound together.

The close spacing between the super-star cluster sources warrants a very efficient thermalization of all their winds and supernova explosions, leading to the high central overpressure that is to drive both the superbubble and in some cases the SGW. The outflow is fully defined by three quantities: the mass and mechanical energy deposition rates (hereafter $\dot{M}_{SB}$ and $\dot{E}_{SB}$) and the radius that encompasses the newly born sources (R_{SB}).

The total mass and energy deposition rates define the central temperature and thus the sound speed c_{SB}

$$T_{SB} = \frac{0.299\mu}{k}\frac{\dot{E}_{SB}}{\dot{M}_{SB}}, \tag{1}$$

where μ is the mean mass per particle and k the Boltzmann constant. On the other hand, the density of matter streaming out of R_{SB} is:

$$\rho = \frac{\dot{M}_{SB}}{4\pi R_{SB}^2 c_{SB}}, \tag{2}$$

Thus at R_{SB} (see Chevalier & Clegg 1985; hereafter CC85), the ratio of thermal and kinetic energy flux to the total flux is

$$F_{th}/F_{tot} = \frac{\frac{1}{\gamma-1}\frac{P}{\rho}}{\frac{u^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho}} = \frac{9}{20} \tag{3}$$

$$F_k/F_{tot} = \frac{u^2/2}{\frac{u^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho}} = \frac{1}{4}. \tag{4}$$

There is however a rapid evolution as matter streams away from the central starburst. After crossing $r = R_{SB}$ the gas is immediately accelerated by the steep pressure gradients and rapidly reaches its terminal velocity ($V_t \sim 2c_{SB}$). This is due to a fast conversion of thermal energy, into kinetic energy of the resultant wind.

In a recent communication (Silich et al. 2003), we have revised the properties of SGWs by solving the flow equations dropping the assumption of an adiabatic flow made by Chevalier & Clegg (1985). In this case, the steady-state solution results from solving

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(\rho u r^2\right) = 0, \tag{5}$$

$$\rho u \frac{\mathrm{d}u}{\mathrm{d}r} = -\frac{\mathrm{d}P}{\mathrm{d}r}, \tag{6}$$

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left[\rho u r^2\left(\frac{u^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho}\right)\right] = -Q, \tag{7}$$

where Q is the cooling rate ($Q = n^2\Lambda$), n is the wind number density and Λ is the cooling function. The main effect is to largely reduce the size of the X-ray emitting zone, particularly in the case of powerful and compact starbursts.

The energy dumped by the central starburst, is to cause a major impact on the surrounding gas. 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 free wind takes distance to the star cluster boundary, its density, temperature and thermal pressure will drop as r^{-2}, $r^{-4/3}$ and $r^{-10/3}$, respectively (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 become lower than that of the surrounding gas, as it is the case 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 rapidly causes the development of a reverse shock, the thermalization of the wind kinetic energy and a much reduced size of the FWR. 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 and to a supergalactic wind with properties (density, temperature and thermal pressure) in principle similar to those derived by CC85 for a free wind.

3. THE PROPERTIES OF SUPERBUBBLES

Given the extreme violence of the ejection process, either through supernova explosions or strong stellar winds, the presence of strong reverse shocks assures that upon the thermalization the ejected matter would reach temperatures ($T \sim 10^7 - 10^8$ K) that would strongly inhibit recombination and thus the detection of the newly processed material at optical frequencies. Furthermore, it is now well understood that it is this hot high pressure gas the one that fills the interior of superbubbles and that drives the outer shock that sweeps and accelerates the surrounding ISM. It has then become clear in recent years that the metallicity detected in blue compact dwarfs, the same as in all other galaxies, results from their previous history of star formation and has nothing to do with the metals presently ejected by their powerful starbursts. The continuous energy input rate that in the coeval starburst model lasts until the last 8 $M_\odot$ star explodes as supernova ($t \sim 4 \times 10^7$ yr) or it extends until the star formation phase is over in the continuous star formation model, reassures that the high temperature of the ejected matter is maintained above the recombination limit ($T \sim 10^6$ K) allowing superbubbles to reach dimensions in excess of 1 kpc. During this phase the first step towards mixing takes place. About 10% of the interstellar matter swept up and stored in the expanding supershell, becomes thermally evaporated and thus injected into the superbubble interior during the evolution. As the evaporated matter streams into the superbubble it acquires a similar temperature to that of the supernova ejected gas. Under such conditions mixing is expected to become a rapid process. This is because the large temperatures favor diffusion, and also because the large sound speed ensures an efficient stirring between the two gases. Mixing of the evaporated ISM with the ejected metals lowers the metallicity of the superbubble interior. Silich et al.(2001) have predicted the values to be expected from X-ray observations during this phase if one uses either iron or oxygen as tracers. There is however, no diffusion of the highly metal enriched superbubble gas over the matter either in the expanding shell or its immediate surroundings (see Tenorio-Tagle 1996, Oey 2003). For a true enrichment of the ISM one would have to wait for cooling and the large-scale dispersal of the newly processed metals. This may take a few times 10^8 years.

The high internal pressure (P_{int}) resultant from the thermalization of the fast ejecta at the reverse shock drives the outer shock to collect the surrounding ISM of density (ρ) into a dense shell. This in a constant density medium leads to a continuous deceleration of the remnant. However, if the evolution takes place in a disk-like configuration, and the density falls off steeply in the direction perpendicular to the plane of the galaxy, much more rapidly than the fall of the pressure, then the shock will be force to accelerate in the direction of the density gradient. This is the moment of breakout (Kompaneets 1960). Upon breakout, the section of the shell following the shock will also experience a sudden acceleration, fact that will promote the development of Rayleigh - Taylor instabilities that will lead to its fragmentation. The hot gas filling the remnant interior will then be able to stream between fragments, venting the high pressure of the remnant either into the extended halo of the galaxy, forming a large superbubble, or into the IGM in the case of a flattened disk-like system, leading eventually to a SGW. In both cases, the evolving remnant would appear more and more displaced from the galaxy disk, fact that has lead to the confusion between superbubbles and SGWs.

Take for example the case of NGC 1569 thoroughly reviewed recently by Martin et al. (2002). There the X-ray emission detected by Chandra, clearly looks displaced from the HI disk. The authors found a starburst age of $\sim 10 - 20 \times 10^6$ yr. Also, using oxygen as tracer, they ascribed a metallicity to the X-ray cloud of at least 2 $Z_\odot$. This implies a total oxygen content of some 34,000 $M_\odot$. All of these results are in excellent agreement with the results of the evolution of superbubbles obtained by Silich et al. (2001).

NGC 1569 is clearly not undergoing a supergalactic wind. This issue was also addressed by Martin et al., who noticed that the X-ray emissivity is fairly even, as expected in superbubbles, instead of stratified, given the rapid drop in density and temperature away from the central source, as predicted for SGWs. Furthermore, they also noticed that the X-ray emission implies an interaction with the halo of the galaxy, even in the locations where the HI observations have failed to detect it. An important issue that may again lead to confusion is the fact that NGC 1569 with a total mass of a few $\times 10^8$ $M_\odot$ is supposed to have a mechanical energy input rate above the threshold required for mass ejection into the IGM (see Silich & Tenorio-Tagle 2001). The same appears to be the case for other massive galaxies. This could, in principle, be used as an argument in favour of an eventual development of a SGW. Note however, that although the threshold imposed by the existence of a galaxy halo has brought the threshold up to three orders of magnitude higher than that envisaged for fattened galaxy disks (see Mac Low & Ferrara 1999), it is still a lower limit to mass ejection.

4. THE ENERGY LIMIT FOR MASS EJECTION INTO THE IGM

The energy input rates derived by Silich & Tenorio-Tagle (2001), despite the fact of being orders of magnitude above the limits derived by Mac Low & Ferrara (1999), are lower limits to the amounts required for expelling matter from a galaxy. Particularly because only one component of the ISM was considered and because the central densities adopted are well below the values expected for the star forming cloud where the starburst originated. Our estimates thus neglect the effect of the starburst plowing into the parental cloud material. These are lower limits also because we adopted a constant energy input rate (see Strickland & Stevens 2000; Silich et al. 2002) and because our approach neglects the presence of a magnetic field which could also inhibit expansion (Tomisaka 1998). It is thus not surprising that some galaxies like NGC 1569, Haro 2, IZw18 and Markarian 49 (see Legrand et al. 2001), lie slightly above the ejection limit while their physical structure is clearly that of bound superbubbles. However, note that this is not the case for M82, where with an energy input rate of 3×10^{42} and an ISM mass around 10^9 $M_\odot$, lies more than an order of magnitude above the limit prescribed by Silich

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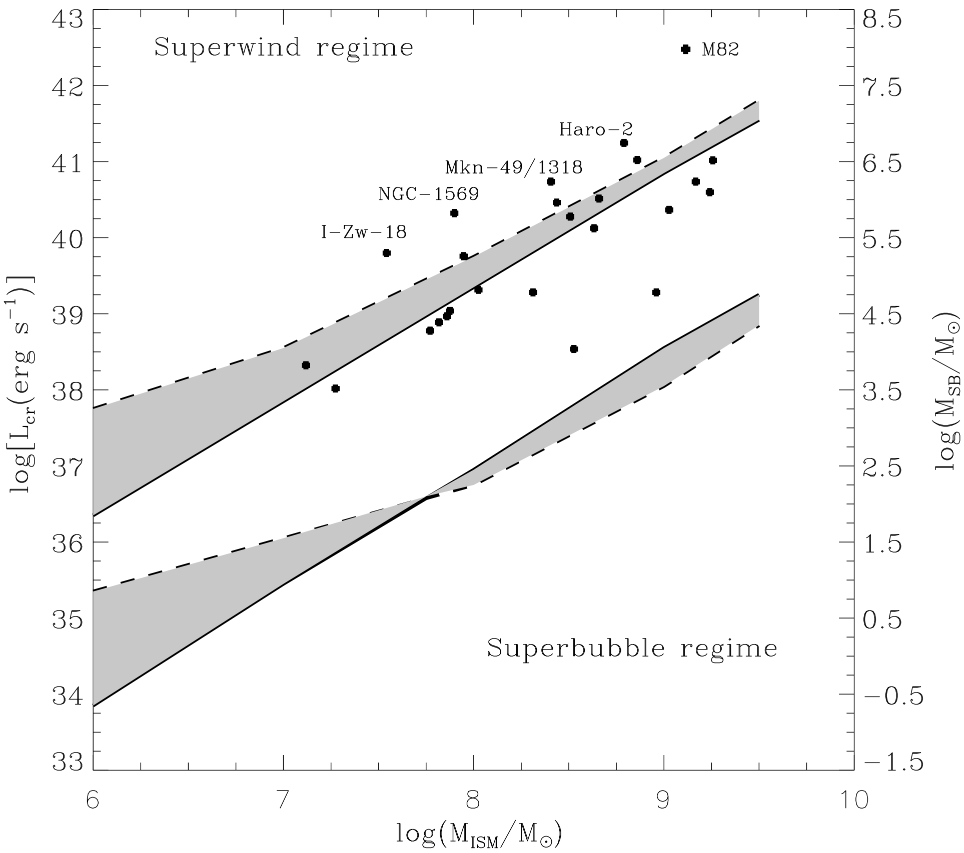

Fig. 1. Numerical energy estimates. The log of the critical mechanical luminosity (left axis), and of the starburst mass (right-hand side axis), required to eject matter from galaxies with a M_{ISM} in the range 10^6 – 10^9 M$_\odot$. The lower limit estimates are shown for galaxies with extreme values of ϵ (= 0 and 0.9) and for two values of the intergalactic pressure $P_{IGM}/k = 1$ cm^{-3} K (solid lines) and $P_{IGM}/k = 100$ cm^{-3} K (dashed lines). The resolution of our numerical search is $\Delta log L_{cr} = 0.1$. Each line should be considered separately as they divide the parameter space into two distinct regions: a region of no mass loss that is found below the line and a region in which blowout and mass ejection occur that is found above the line. Figure adapted from Silich & Tenorio-Tagle (2001). The location of several local dwarf galaxies as studied by Legrand et al. 2001 and that of M82 are indicated in the figure.

& Tenorio-Tagle (2001) and is thus a true example of a supergalactic wind.

The indisputable presence of metals (in whatever abundance) in galaxies implies that the supernova products cannot be lost in all cases. Note in particular that many well known disk galaxies have a high metal abundance and a large number of centers of star formation. Most of these exciting star clusters are more massive than the 10^4 M$_\odot$ lower limit established by Mac Low & Ferrara (1999) and Silich & Tenorio-Tagle (2001) as the minimum starburst mass required to cause mass ejection in the case of disk-like systems. This lower limit for disk-like galaxies with M$_{ISM} \leq 10^9$ M$_\odot$ (see Figure 1) implies that starbursts even smaller than the Orion cluster would break through the galaxy outer boundary and eject their supernova products into the intergalactic medium. Nevertheless, galaxies can avoid losing all their freshly produced metals by having a halo component, neglected in former studies, that acts as the barrier to the loss of the new metals.

The extended gaseous haloes, despite acting as the barrier to the loss of the new metals, have rather low densities ($< n_{halo} > \leq 10^{-3}$ cm^{-3}) and thus have a long recombination time ($t_{rec} = 1/(\alpha n_{halo})$; where α is the recombination coefficient) that can easily exceed the life time of the HII region ($t_{HII} = 10^7$ yr) produced by the starburst. In such a case, the haloes may remain undetected at radio and optical frequencies (see Tenorio-Tagle et al. 1999, Martin et al. 2002), until large volumes are collected into the expanding supershells. Note that the continuous Ω shape that supershells present in a number of galaxies, while remaining attached to the central starburst, and their small expansion velocity (comparable or smaller than the escape velocity of their host galaxy) imply that the mechanical energy of the star cluster is plowing into a continuous, as yet undetected medium. Supershells crossing the outer galaxy boundary into the IGM, should become Rayleigh Taylor unstable and rapidly fragment. This will then favour the streaming of the hot superbubble interior and thus the development of a supergalactic wind. Most galaxies in the local universe, including those with a low metal abundance, however, do not present as in M82, a clear evidence of having evolved into such a phase.

5. CONCLUDING REMARKS

- Superbubbles, bound by a large-scale expanding supershell, are powered by the thermalized ejected matter and thus present a very even temperature distribution. On the other hand, supergalactic winds, given their stratification in density and temperature aught to present a stratified X-ray emission.

- The metallicity within the interior of superbubbles changes rapidly with time. It exceeds $Z_{\odot}$, particularly within the first 10 - 20 Myr of the evolution.

- The development of supergalactic winds depends drastically on the distribution of ISM both in the host galaxy disk and in the halo. Apart from M82, there is no strong evidence of a supergalactic wind in the Local Universe.

-Supergalactic winds driven by compact and powerful starbursts are subjected to strong radiative cooling, which modifies their temperature distribution and thus their X-ray appearance. Radiative cooling reduces drastically the size of the extended X-ray emitting zone favouring instead the formation of a rapidly expanding photoionized envelope. This may show up as low intensity broad emission lines associated with luminous starbursts.

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