SUPERGALACTIC WINDS DRIVEN BY MULTIPLE SUPER–STAR CLUSTERS

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ABSTRACT

Here we present two-dimensional hydrodynamic calculations of free expanding supergalactic winds, taking into consideration strong radiative cooling. Our main premise is that supergalactic winds are powered by collections of super–star clusters, each of which is a source of a high-metallicity supersonic diverging outflow. The interaction of winds from neighboring super–star clusters is shown here to lead to a collection of stationary oblique shocks and crossing shocks, able to structure the general outflow into a network of dense and cold, kiloparsec long filaments that originate near the base of the outflow. The shocks also lead to extended regions of diffuse soft X-ray emission and, furthermore, to channel the outflow with a high degree of collimation into the intergalactic medium.

Subject headings: galaxies: ISM — galaxies: starburst — ISM: bubbles — X-rays: general

1. INTRODUCTION

Supergalactic winds (SGWs; see Heckman 2002), as first envisaged by Chevalier & Clegg (1985, hereafter CC85), freely flow from the nuclear starburst region of a galaxy into intergalactic space. The flow originally thought to behave in an adiabatic manner has recently been shown to be strongly affected by radiative cooling, particularly for powerful ($>10^{41}$ erg s$^{-1}$) and compact starbursts (see Silich et al. 2003, hereafter Paper I). Radiative cooling does not disturb the velocity of the outflow or the expected density drop ($\sim r^{-2}$) acquired as the flow moves from the massive central cluster. Rapid cooling, however, brings the temperature down in regions close to the starburst, favoring rapid recombinant ionization and thus making the fast-streaming outflow an easy target of the UV radiation generated by the central stars. The prediction is then a much reduced size of the X-ray–emitting zone and a fast-moving Hα region gas originating close to the central starburst.

M82, with its wind striking the “Hα cap” at 10 kpc from the central source (see Devine & Bally 1999), is without a doubt the best example of a SGW in the local universe, injecting its newly processed metals into the intergalactic medium (IGM). The central biconical wind in M82, however, presents an intricate structure that has little to do with the outcome from models of superwinds. In particular, the X-ray and Hα filamentary structure, as well as their spatial coincidence, at present have no explanation. As stated by Strickland & Stevens (2000), the predicted X-ray luminosity, even using the adiabatic model of CC85, falls short by more than 3 orders of magnitude below the observed value. Strickland, Ponman, & Stevens (1997) also showed that the entropy of the X-ray–emitting gas increases with distance from the plane of the galaxy, a fact that is inconsistent with an adiabatic outflow model. On the other hand, the Hα filamentary structure, beautifully evidenced by Subaru (see Ohyama et al. 2002 and references therein), is clearly not limb-brightened and originates right at the base of the outflow, reaching several kiloparsecs in a direction almost perpendicular to the galaxy plane. These facts are also very different from the superbubble features calculated by Suchkov et al. (1994), in which a complex filamentary structure develops at large distances (several kiloparsecs) from the galaxy disk as a result of matter entraining the hot superbubble. There should in fact be very little resemblance between supergalactic winds freely expanding into the IGM and the calculations mentioned above in which a supershell always contains the possible outflow of the superbubble interior and thus inhibits the development of a supergalactic wind.

So far, all calculations in the literature have assumed that the energy deposition arises from a single central cluster that spans several tens of parsecs, the typical size of a starburst. However, recent optical, radio continuum, IR, and UV observations (Ho 1997; Johnson et al. 2001; Colina et al. 2002; Larsen & Richtler 2000; Kobulnicky & Johnson 1999) have revealed a number of unusually compact young stellar clusters. These overwhelmingly luminous concentrations of stars present a typical half-light radius of about 3 pc and a mass that ranges from several times $10^4 M_\odot$ to a few $10^6 M_\odot$. Clearly, these units of star formation (super–star clusters; SSCs) are very different from what was usually assumed to be a typical starburst. Several of these entities have now been identified within a single starburst nucleus. For example, there are about 100 of them, composing a flattened distribution of 150 pc radius at the center of M82 (see de Grijs, O’Connell, & Gallagher 2001; O’Connell et al. 1995), at least four within the nuclear zone of NGC 253 (Watson et al. 1996), and many of them in the Antennae galaxy (Whitmore et al. 1999).

Here we investigate the effects that the presence of several of these young compact clusters in a galaxy nucleus may have on the inner structure of well-developed or freely expanding SGWs. Several aspects are considered in this two-dimensional first approach to the three-dimensional interaction of multiple powerful winds. Among these, the metallicity of the superwind matter is shown here to have a profound impact on the inner structure of SGWs.

Here we study the interaction of several strong winds emanating from a collection of nearby super–star clusters, together causing the development of an extended region in

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which a plethora of crossing shocks collimate the general outflow while giving rise to an important soft X-ray contribution at large distances from the starburst nuclei: an extended region in which the layers of strong direct wind interactions lead, under strong radiative cooling, to a well-developed network of elongated filaments. Section 2 displays our two-dimensional calculations that use CC85 as an initial condition in each of the super-star clusters. The evolution leads to multiple interactions, and the outcome of these, depending on the local values of density, temperature, and metallicity, define when the flow is affected by strong radiative cooling. Section 3 discusses some of the observational consequences of such well-collimated and structured outflows, in particular, the resultant filling factor for different gas phases.

2. THE INTERACTION OF WINDS FROM SUPER–STAR CLUSTERS

There are two different evolutionary stages in the remnants produced by the large mechanical energy input rate associated with nuclear starbursts. The first, the superbubble phase, is that during which a large-scale remnant evolves within the ISM, either within the disk or within the halo of the host galaxy. The second phase, the freely expanding supergalactic wind, is one in which an open channel in the ISM allows the supernova matter to freely stream into the intergalactic medium.

Whether one assumes a central source or multiple SSCs composing a starburst nucleus, the initial interaction with the host galaxy ISM will be rather similar. In particular, both sources of energy will lead to the development of a leading shock, able to sweep the surrounding ISM into a large-scale supershell, while a reverse shock will cause the full thermalization of the matter violently ejected by the central source or the multiple stellar clusters (see, for example, Fig. 1 in Heckman, Armus, & Miley 1990).

In both cases the thermalized hot gas within the superbubble will power the leading shock and thus promote the growth of a remnant able to eventually exceed the dimensions of the galaxy disk, causing via Rayleigh-Taylor instabilities the fragmentation and disruption of the supershell of swept-up matter (see Fig. 4 in Tenorio-Tagle & Bodenheimer 1988).

If one considers the presence of an extended halo (see Silich & Tenorio-Tagle 1998, 2001), the thermalized wind energy will generate an even larger supershell (see, for example, Fig. 6 in Strickland & Stevens 2000), the velocity of which will continuously decay as more halo matter is incorporated. The presence of extended halos (see, e.g., Melo et al. 2002) is also supported by the existence of large-scale supershells in a large variety of galaxies (see, for example, Oey et al. 2002 and Marlowe et al. 1995).

Note that a supergalactic wind does not develop until the remnant exceeds the dimensions of the galaxy disk or, in the case of an extended halo, until the superbubble reaches the outskirts of the galaxy (for a review, see Heckman 2002). At this moment, the leading and reverse shocks cease to exist, and the metals ejected by the star clusters will freely move into the intergalactic medium, causing its contamination. It is also at this stage, once a channel has been carved in the ISM and once the superwind has developed, that major differences will arise from the assumption of a single or a multiple source of energy.

1. In the case of a single compact source of energy, the free expanding wind has recently been found to be subjected to strong radiative cooling (see Paper I). Thus, the adiabatic model of Chevalier & Clegg (1985), used to calculate the extended X-ray emission of superwinds, leads to large overestimates. More realistic calculations, accounting for radiative cooling, have shown a much reduced volume, of only a few times the size of the starburst nucleus, able to generate X-rays. In this framework it is hard to understand the extended (more than 3 kpc long) X-ray emission of M82, a source that presents a more than 10 kpc long open channel into the intergalactic medium and that clearly is in the supergalactic wind stage.

2. Models with a single source also predict a strong H\textalpha emission arising from the lateral walls of the disrupted supershell, continuously impacted by the UV radiation arising from the central source (see, for example, Suchkov et al. 1994; Tenorio-Tagle & Muñoz Tuñón 1997, 1998). The emission in such a case should be strongly limb-brightened.

3. Most models (perhaps with the sole exception of Tenorio-Tagle & Muñoz Tuñón 1997, 1998, which accounts 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 & Ikeuchi 1988; Suchkov et al. 1994). This could measure several kiloparsecs in radius and is very different from the 150 pc radius estimated for the central perturbed area of M82.

The H\textalpha emission of M82 is not limb-brightened and arises from distinct filaments that emanate from the base of the outflow. This last point is also relevant, as many models attempt to explain the filamentary structure with shell instabilities or with matter entraining the supershell at high distances from the galaxy plane (see Suchkov et al. 1994).

In §§ 2.1–2.4 we derive the properties of supergalactic winds powered by multiple super–star clusters and stress the main differences in the resultant structure with respect to models that assume a single source.

2.1. The High-Metallicity Outflow of Supergalactic Winds

Whether one considers one or multiple sources, the amount of metals expected from massive starbursts, and thus to be found within SGWs, depends strongly on the assumed stellar evolution models. Two extreme possibilities were investigated by Silich et al. (2001), taking into consideration models with and without stellar winds by Maeder (1992), Woosley, Langer, & Weaver (1993), and Thielemann, Nomoto, & Hashimoto (1993) (see also Pilyugin & Edmunds 1996). The results indicate, first of all, that almost 40% of the mass gone into stars is violently returned to the surrounding medium by means of winds and supernovae. Of this, about 4% is in oxygen for the case of models without winds, and 1% is in oxygen for models that include winds. In either case, if one assumes that the metals mix efficiently with the stellar hydrogen envelopes of the progenitors, within the radius that encompasses the stellar cluster, then the metallicity of the superwind can be calculated. As shown by Silich et al. (2001) for the case of superbubbles, this reaches supersolar values in all considered cases, showing a maximum within the first 7–8 Myr of the evolution. Such values have recently been confirmed through X-ray observations by Martin, Kobulnicky, & Heckman (2002) for NGC 1569.
Here we consider the winds from several identical SSCs, each with a mechanical energy deposition rate equal to $10^{41}$ ergs 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 & Clegg (1985). The separation between the sources is clearly arbitrary. We have considered two different configurations. The first one has three SSCs placed at 60 and 90 pc from the central one, all of them sitting on a plane. A second configuration considers only two sources sitting at 30 and 60 pc from the symmetry axis. Several calculations were made to ensure that the spatial resolution used led to a convergent solution. All calculations presented here were made with the same numerical resolution of half a parsec, and all of them were made with an open boundary along the grid outer edge. The time-dependent calculations do not consider thermal conductivity but do account for radiative cooling, with a cooling law (Raymond, Cox, & Smith 1976) scaled to the metallicity assumed for every case. Here we present the results of different cases for which the assumed metallicity of the winds was set equal to 3 and 10 $Z_\odot$, justified by the high-metallicity outflows expected from massive star formation (see Fig. 1).

In all cases it is assumed that at the heart of each SSC, within the region that encompasses each of the recently formed stellar clusters ($R_{SB}$), the matter ejected by strong stellar winds and supernova explosions is fully thermalized (CC85; see also Canto, Raga, & Rodriguez 2000 and Raga et al. 2001). This generates the large overpressure responsible for the mechanical luminosity associated with each of the super–star clusters. Within each star cluster region, the mean total mechanical energy $E_{SB}$ and mass $M_{SB}$ deposition rates, control, together with the actual size of the star-forming region $R_{SB}$, the properties of the resultant outflow. The total mass and energy deposition rates define the central temperature $T_{SB}$ and thus the sound speed $c_{SB}$ at the cluster boundary. As shown by CC85 at the boundary $r = R_{SB}$, the flow starts expanding with its own sound speed. There is, however, a rapid evolution, and as matter streams away it is immediately accelerated by the steep pressure gradients and rapidly reaches its terminal velocity ($V_\infty \approx 2c_{SB}$). This is due to a fast conversion of thermal energy into kinetic energy of the resultant winds. In this way, as the winds expand, their density, temperature, and thermal pressure will drop as $r^{-2}$, $r^{-4/3}$, and $r^{-10/3}$, respectively (see CC85). The flow is then exposed to suffer multiple interactions with neighboring winds, and, as shown in Paper I, it is 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 ($T \approx 10^4$ K), highly supersonic streams (see Paper I).

2.3. The Structure of Supergalactic Winds

Figure 2 compares the initial stages of cases 1 and 2 that consider three equally powerful ($L_{SB} = 10^{41}$ ergs s$^{-1}$) super–star clusters sitting at 0, 60, and 90 pc from the symmetry axis. All of them, with a $R_{SB} = 5$ pc, almost immediately produce a stream with a terminal velocity equal to 1000 km s$^{-1}$. The only difference between the two cases is the assumed metallicity set equal to 3 $Z_\odot$ in case 1 (top panels) and 10 $Z_\odot$ in case 2 (bottom panels). At $t = 0$ yr the three clusters are embedded in a uniform low-density ($\rho = 10^{-26}$ g

Fig. 1.—Metallicity of the ejected matter. The metallicity of freely streaming outflows produced by massive bursts of star formation (in solar units) is plotted against the evolutionary time. The outflow emanates from a coeval starburst able to thermalize and mix all the newly processed metals with the stellar hydrogen envelopes of the progenitors. The curve is derived for stellar evolution models with winds (see Silich et al. 2001) using oxygen as a tracer. The metallicity of the outflow reaches supersolar values during most of the evolution and is strongly reduced down to the original assumed ISM values once the production of oxygen reaches its yield.

The large metallicities expected from massive star clusters have a strong impact on the cooling properties of the outflow and thus also on the observational properties of freely expanding superwinds. Figure 1 shows the run of the expected metallicity of the matter ejected by a massive burst of stellar formation, using oxygen as tracer and stellar evolution models with winds, as a function of time. The estimate is for a coeval starburst powered during 40 Myr of evolution (until the last 8 $M_\odot$ star explodes as a supernova in a coeval starburst model). The outflow, before the supernova era, will display a metallicity similar to that of the gas cloud out of which the starburst formed. Thus, the gas ejected first presents the metallicity assumed here for the host galaxy ($Z_{ISM} = 0.1 Z_\odot$). The supernova products, however, rapidly enhance the metallicity of the outflow, reaching values well above $Z_\odot$ for at least 20 Myr of the evolution. Afterward, once the yield is reached, the outflow steadily approaches the metallicity values of the host galaxy. Starburst models, with single or multiple energy sources, are to account for the high metallicities emanating from the massive centers of star formation to derive in a consistent manner the impact of radiative cooling in the resultant outflows.

2.2. Boundary and Initial Conditions

Several two-dimensional calculations using CC85 adiabatic flows as an initial condition have been performed with the explicit Eulerian finite difference code described by Tenorio-Tagle & Muñoz-Tuñón (1997, 1998). This has been adapted to allow for the continuous injection of multiple winds (see below).
Thus, our calculations do not address the development of a superbubble, or 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 super–star clusters, and we center our attention on the interaction of the supersonic outflows.

Figure 2 shows the resultant initial stages of cases 1 and 2. The various panels display the run of density and velocity (left panels) and that of temperature (next four panels) in four temperature ranges: The regime of H recombination $10^4–10^5$ K, followed by two regimes of soft X-ray emission, $10^5–10^6$ 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 a steep gradient, both in density or in temperature and velocity, and thus indicate the presence of shocks and of rapid cooling zones. In the temperature plots one can determine the distance (~30 pc in case 1 and 15 pc in case 2) within the diverging outflows emanating from each of the super–star clusters, at which strong radiative cooling (in agreement with our analytical estimates in Paper I) becomes important in the two cases.

The interaction of neighboring supersonic winds causes the immediate formation of their respective reverse shocks 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 with radiative cooling how broad or narrow the high-pressure zones behind the reverse shocks are going to be. Radiative cooling occurs in every parcel of gas at the rate prescribed by its local density, temperature, and metallicity. If cooling is avoided at least partially or temporarily, as in the first case, the high-pressure region between the reverse shocks would drive them against the incoming streams, and very shortly they would acquire an oblique standing stable configuration to be retained for as long as the winds continue to interact (see Fig. 2, top panels).

This also happens if cooling is fast enough; the oblique reverse shocks rapidly acquire a standing location. However, in these cases the loss of temperature behind the shocks is compensated by gas condensation, leading, as in the second case (see Fig. 2, bottom panels), 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 exacerbated. The dense structures are then launched at considerable speeds (~several hundreds of km s$^{-1}$) from zones near the plane of the galaxy (see Fig. 2, bottom panels). These dense and cold structures are easy targets for the UV radiation produced by the super–star clusters, and thus, on cooling and recombination, are likely to become photoionized. Note, however, that as the free winds continue to strike on 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: (1) partial thermalization and (2) 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 toward the shocks. This leads both to an efficient collimation of the outflow 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 (kiloparsecs) 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 and thus that will radiate in different energy bands.

Figures 3 and 4 show the time sequence of cases 1 (with $Z = 3 Z_{\odot}$) and 2 (with $Z = 10 Z_{\odot}$), respectively, until they reach dimensions of 1 kpc, together with the final temperature structure split into the four temperature regimes considered earlier (last four panels). The stream of gas behind the reverse shocks eventually leads to the establishment of crossing shocks at the tips of the oblique structures (see Fig. 3), which are also to become stationary as the flow is effectively channeled into the IGM.

As in the case of colliding stellar winds from binary systems (see Stevens, Blondin, & Pollock 1992) a variety of dynamical instabilities are found to dominate the shocked region, particularly when strong radiative cooling sets in (see Fig. 4). These lead to the various loops and twists along the dense filamentary structures, which nevertheless do not impede, that the outflow reaches large distances from the galaxy plane. The loops and twists along these structures also promote a larger cross section to the incoming free wind and partly thermalized wind and thus lead to regions of enhanced soft X-ray emission clearly associated to the twisted Hα filaments (see Fig. 4).

Figure 5 displays the results from a final case in which two super–star clusters sitting at 30 and 60 pc from the symmetry axis interact to shape the inner structure of a superwind. The calculation also assumes a $Z = 10 Z_{\odot}$. As in case 2, elongated filaments result from the interaction of the high-metallicity winds, channeling most of the energy deposited by the SSCs into the IGM. Note that, as in the preceding cases, about 50% or less of the energy deposited by the most outer SSC is lost in the radial direction, while the rest, as well as that deposited by other energy sources, is fully driven into the IGM.

2.4. Self-collimated Supergalactic Winds

The high degree of collimation attained in our calculations, which composes a SGW from a collection of energetic neighboring super–star clusters, results from the simple fact of having placed the individual wind sources of equal strength, all of them, in a preferential plane. In this way, it becomes irrelevant whether they all sit on a flattened disk or in a ring. As long as they all sit near a preferential plane, the interaction of neighboring supersonic diverging flows will promote the multiple standing reverse oblique shocks and crossing shocks that will unavoidably lead to a remarkably efficient self-collimation: collimation that does not required of a torus or a thick disk of ISM. If all super–star clusters sit on a plane, only a fraction of the energy provided by the ones sitting at the outermost extremes of the cluster distribution will interact with the general ISM. However, most of the energy produced by the collection of sources will be rechanneled by the standing oblique shocks resulting from neighboring interactions to compose a broadband supersonic jet capable of self-collimation. The base of the outflow will then have dimensions similar to the flattened cluster distribution, and as shown above, depending on the individual energetics, proximity, and metallicity, the general outflow is to generate a dense and cold filamentary structure as well as a kiloparsec–extended soft X-ray–emitting region, a rich structure that could not arise if one assumes a free–expanding wind that emanates from a single SSC.

A wider jet structure may be generated in cases in which the population of SSCs do not have the same mass and thus equal mechanical energy input rates. Under such conditions the oblique shocks will present standing configurations more inclined over the less energetic clusters, and this will lead to the fanning and broadening of the outflow and to the inclination of the filamentary pattern.
3. DISCUSSION

From the starburst synthesis models (see Leitherer & Heckman 1995) one knows that a super–star cluster with a total mass in stars (say $M_\ast \sim 10^6 M_\odot$) produces an almost constant ionizing photon flux ($F_{\text{UV}} \sim 10^{53}$ photons s$^{-1}$) during the first few (3–4) Myr, and then it abruptly begins to decrease as $t^{-5}$ as the most massive stars begin to evolve from the main sequence to eventually end up as supernovae. This implies that after 10 Myr of evolution, the ionizing flux would be more than 2 orders of magnitude smaller than its original value, and thus the UV radiation will be unable to ionize the original H $\text{ii}$ region volume, limiting to 10 Myr the duration of the H $\text{ii}$ region phase. On the other hand, the mechanical energy deposition from such a cluster leads to an almost constant value ($\sim 10^{50}$ erg s$^{-1}$) over a much longer time span, as it includes the correlated supernovae from stars down to $8 M_\odot$ with an evolutionary time of 40–50 Myr, and thus the supernova phase is 4 or 5 times longer than the H $\text{ii}$ region phase.

Fig. 3.—Same as Fig. 2, but for $Z = 3 Z_\odot$. The evolutionary time in the four first panels is $1.62 \times 10^5$, $4.17 \times 10^5$, $9.4 \times 10^5$, and $1.25 \times 10^6$ yr. The last four panels show the temperature distribution, as in Fig. 2, for the last calculated model. The size of the plots displays the entire computational grid, 100 pc $\times$ 1 kpc.
Under such circumstances, if one considers a starburst nucleus composed by several SSCs generated at different times, then the time span during which the isotropic winds from these may interact, the coherence phase, is limited to 40 Myr. Within this time, newly born clusters will have the capability of causing the ionization of the structure produced by interacting winds that emanate even from a cluster with an age in excess of 10 Myr. During the coherence phase, some of the SSCs will also be producing highly metallic outflows (see Fig. 1), the interaction of which will lead to a filamentary wind structure.

A comparison of the last calculated time of cases 1 and 2, each with three SSCs dumping $10^{41}$ ergs s$^{-1}$ (see Figs. 3 and 4), when the redirected outflow has reached dimensions of almost 1 kpc, allows for an estimate of the filling factor occupied by gas at different temperatures. The hot ($T \geq 10^5$ K) gas occupies almost 70% in case 1 and 30% in case 2 of the total area. The warm gas ($T \leq 10^5$ K) fills most of the remaining volume, although the dense and cold enhancements evident in Figure 4 occupy about 40% of the superwind cross-sectional view. There is also a small volume around the SSCs that presents temperatures that will allow...
the gas to radiate in the hard X-ray regime (see last two plots in Figs. 3 and 4). This numbers are to be compared with the results from the outflow produced by an equally energetic \((3 \times 10^{41} \text{ ergs s}^{-1})\) single cluster. Following Paper I, we have calculated the temperature distribution and thus the radius at which radiative cooling (assuming \(Z = 3 Z_\odot\)) sets in for a cluster with a radius of 95 pc (the size of the cluster distribution used in cases 1 and 2). The temperature of such a free-streaming outflow plummets to \(10^4\) K at 480 pc (instead of \(\sim 10\) kpc obtained if one assumes an adiabatic flow). In such a case, if one considers a similar volume to that displayed in Figures 3 and 4, then the hot gas \((T \geq 10^5\) K) filling factor will be 37.5\%, and the rest of the volume will be filled with gas capable of being reionized by the stellar photon flux. When comparing the results from single and multiple sources, it is crucial to notice the spatial distribution of the various resultant gaseous phases. Cases with multiple SSCs lead to the spatial coexistence of the X-ray \((T \geq 10^5\) K) and the dense and cold \((T \leq 10^5\) K) emitting filaments (see panels 5 and 6 in Figs. 3 and 4). In the case of a single source

Fig. 5.—Same as Fig. 3, but for \(Z = 10 Z_\odot\). The calculation considers only two super–star clusters far from the symmetry axis. The evolutionary times of the first four panels is \(1.8 \times 10^5, 4.94 \times 10^5, 1.05 \times 10^6, \text{ and } 1.4 \times 10^6\) yr, respectively.
of energy the X-ray-emitting gas is not in direct contact with the cooler medium along the outflow; i.e., the structure of the outflow is concentric, with the X-rays emanating only from the most central regions.

The collimation caused by the various oblique and crossing shocks in the multiple source cases, which makes the superwind avoid the diverging outflow inherent to isotropic single source cases, channels almost 5 times more energy within the computational area considered above. In case 1 the thermal and kinetic energy of the hot phase dominate with 26% and 57%, respectively, over the 17% kinetic energy found in the gas with $T \lesssim 10^5$ K. These numbers are to be compared with the results from the single source case described above that present within a similar computational volume, 68% and 27% as thermal and kinetic energy of the hot gas, while only 5% of the total appears as kinetic energy of the gas with $T \lesssim 10^5$ K.

The origin of the X-rays in nuclear starburst regions and of the filamentary structure, as seen in H$\alpha$ in M82, has been ascribed to features seen in models that consider various stages in the development of hot superbubbles powered by a central starburst: models that present a single reverse shock, an outer supershell, and thus models that have little to do with a free-expanding SGW. Note that if the wind of M82 has reached the H$\alpha$ cap at 10 kpc from the galaxy disk and is expanding with, say, 1000 km s$^{-1}$, then the free-streaming outflow started at least 10 Myr ago. During that time the base of the outflow has managed to preserve a comparatively small dimension (radius $\sim$150 pc), implying a very efficient channeling of the deposited energy in a direction from the disk of the galaxy. There is also growing evidence of large-scale features in starburst galaxies, caused by an important stellar energy input rate and the richness of structure within the ISM. However, in most of the cases the evidence for a freely expanding supergalactic wind is only marginal. In the case of NGC 253, its extended X-ray-emitting bubble is much smaller than the dimensions of the dusty galaxy halo found by Melo et al. (2002), therefore implying that it is still evolving along the superbubble phase. Similar conclusions were drawn by Martin et al. (2002) for NGC 1569: "The X-ray color variations in the halo are inconsistent with a free-streaming wind and probably reveal the location of shocks created by the interaction of the wind with a gaseous halo." Several more dwarf starburst galaxies were considered by Legrand et al. (2001) in which the energetics inferred from the central clusters were compared with the limit for mass ejection derived by Silich & Tenorio-Tagle (2001). In all considered cases the bulk of the galaxy sample lies below the limit required to reach the galaxies’ outskirts.

From the results of § 2, it is clear that the inner structure of supergalactic winds strongly depends on the energy and mass deposition history. In particular, we have shown that the richness of structure is largely enhanced when the presence of super-star clusters, their powerful winds, and possible interaction within a single starburst nucleus are taken into consideration. These considerations open a new set of possibilities. Issues such as the intensity of star formation in every super-star cluster, which defines their mechanical luminosity, their age, which also impacts on the metallicity of the ejected matter, as well as the number of super-star clusters, their compactness, and their position within a starburst nucleus, are all relevant new parameters that allow for the coexistence of X-rays and optical-emitting features, even at large distances from the source of energy.

From our results it is clear that a plethora of structure, both in X-rays and in the optical line regime, may originate from the hydrodynamical interaction of multiple winds. The interaction leads to multiple-standing oblique (reverse) shocks and crossing shocks able to collimate the outflow from the plane of the galaxy. In our two-dimensional simulations, these are surfaces that become oblique to the incoming streams and thus evolve into oblique shocks that only partly thermalize the kinetic energy of the winds, causing a substantial X-ray emission at large distances from the galaxy plane: surfaces that simultaneously 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 stream from the plane of the galaxy to kiloparsec scales. Under many circumstances these filaments develop right at the base of the outflow, and for all cases the prediction is that they are highly metallic. Note that the speed with which the calculated filaments rise above the galaxy plane is $\sim$600 km s$^{-1}$, a value in excellent agreement with the measured deprojected velocities of the filaments in M82 (Shopbell & Bland-Hawthorn 1998).

Hydrodynamic instabilities also play a major role in the filamentary structure. Nonlinear thin-shell instabilities, as studied by Vishniac (1994), as well as Kelvin-Helmholtz instabilities, broaden, twist, and generally shape the filaments as these stream upward and reach kiloparsec scales. The broadening of the filaments causes their interaction with the free winds, further thermalizing the rapid stream while leading to the development of soft X-ray-emitting zones that envelop the densest structures.

The surfaces that develop at the plane of interaction between two wind sources are depicted as vertical structures in our two-dimensional approach. From these, the only real vertical structure is the filament that forms along the symmetry axis in our last case. This results from the convergence of multiple winds arising from super-star clusters sitting on a ring 30 pc from the symmetry axis. It is indeed necessary to perform our calculations in three dimensions to see the final outcome. Note, however, that the lateral side of all interaction planes will be launched into the highest pressure regions, i.e., close to the base of the interaction, and thus it is very likely that they would be destroyed by the collision with other similar structures arising from other interaction planes. The final outcome is thus expected to be very similar to that depicted by our two-dimensional simulations. Nevertheless, three-dimensional simulations are now underway and will also consider a variety of stellar masses and ages of the super-star clusters, as well as different locations and numbers within a starburst region.

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