1. INTRODUCTION

Supergalactic winds (SGWs) are a very important mechanism in the evolution of the universe. Lynds & Sandage (1963) found a large outflow in M82 and gave the first definition of a starburst. They proposed that material was ejected from the nuclear regions as the consequence of a supernova (SN) explosion. Different analytical models have been put forward to explain the so-called SGWs; see, e.g., the work of Chevalier & Clegg (1985), Tomisaka & Ikeuchi (1988), Heckman (1990), Leitherer & Heckman (1995), Strickland & Stevens (2000), Canto et al. (2000), Tenorio-Tagle et al. (2003), and Cooper et al. (2008).

In the nearest starbursts, Lynds & Sandage have shown that the SGWs form through the collective effects of many individual stellar cluster winds, which are in turn formed by the collective effect of many individual stellar winds.

The best-studied starburst galaxy is M82. It has an extended, biconical filamentary structure in the optical (Shopbell & Bland-Hawthorn 1998; Ohyama et al. 2002). This optical emission is embedded in a pool of soft X-ray emission, detected with the Chandra X-Ray Observatory (Griffiths et al. 2000), as well as with XMM-Newton (Stevens et al. 2003). This X-ray emission extends several kiloparsecs away from the nuclear region, into the intergalactic medium (IGM).

With the Hubble Space Telescope (HST), it has become possible to isolate the building blocks of some starbursts: super stellar clusters (SSCs). These objects are very massive and dense stellar clusters, with masses in excess of $10^6 M_\odot$ enclosed in radii of 3–10 pc. They are young, and they typically contain from ~100 up to ~$10^4$ OB stars. In M82, the SSC Hα luminosities are in the range of $(0.01–23) \times 10^{38}$ erg s$^{-1}$ (Melo et al. 2005). These authors cataloged 197 SSCs with masses in the $10^4 M_\odot < M < 10^6 M_\odot$ range in M82. This exceptional density of massive clusters (620 kpc$^2$) produces a scenario suitable for a study of the interaction between cluster winds.

The differences in the populations of SSCs of several starburst galaxies can help us to understand which properties are more important for producing filaments. For instance, NGC 253, which does not show a clear filamentary structure (Rice 1993), has a significantly lower SSC mass-loss rate than does M82. However, other authors claim that the absence of filamentary structure in this galactic wind is simply a result of not having deep enough Hα observations of this object (Hoopes et al. 2005). In NGC 253, Melo (2005) cataloged a total of 48 SSCs and found an average distance between them of 31 pc, in contrast with the mean separation between SSCs found in M82, which is 12 pc. In M82, a rich structure of filaments extending out from the galactic plane is present. There are many other examples, such as NGC 1569 (Anders et al. 2004; Westmoquette et al. 2008) and M83 (Harris et al. 2001), that have a high density of SSCs with similar masses to those of M82.

Tenorio-Tagle et al. (2003) showed that the interaction of stellar winds from a collection of energetic, neighboring SSCs could form a filamentary structure similar to the one observed in M82. These authors propose that such filaments form by means of SN explosions that expel a huge amount of heavy elements into the interstellar medium (ISM), thus enhancing the radiative cooling of the outflows.

In their model, Tenorio-Tagle et al. (2003) explained the SGW structure as a consequence of the interaction of winds from very close SSCs, in which stationary oblique shocks are responsible for shaping the material into dense, cold, kiloparsec-sized filaments. More recently, Cooper et al. (2008) presented a numerical study of a starburst-driven galactic wind. Their setup consisted of a series of neutral dense clouds placed in the galaxy disk. The dense clouds are swept up by the main shock wave, leaving behind a filamentary structure.

In the present paper, we discuss models for the formation of filamentary structures as the result of the interaction between
mass-loss rate $\dot{m}$ (number of clusters per unit volume). For the sake of simplicity, in Rodriguez-Gonzalez et al. 2007), the stratified ISM present in the region of the galactic disk. From the wind interactions, and we do not include the effect of the stratified ISM present in the region of the galactic disk.

The paper is organized as follows. In §2, we study which combinations of parameters (mass-loss rate $\dot{M}_{\text{w}}$, cluster wind velocity $v_{\text{w}}$, and separation between nearby stellar clusters $D$) yield a highly radiative SGW flow. In §3 we describe a series of 3D simulations of the interaction of cluster winds in this highly radiative regime. We present predictions of the emission in the optical and X-ray wavelength ranges and compare them with observations of galactic winds (e.g., M82, NGC 253) in §4. Finally, in §5 we present our conclusions.

2. THE FORMATION OF FILAMENTARY STRUCTURES

2.1. General Considerations

The collective effect of the individual stellar winds inside an SSC result in a cluster wind. Outside the outer radius of the cluster (i.e., for radii $r > r_c$, where $r_c$ is the cluster radius), the cluster wind has an approximately constant velocity and a density that falls $\propto r^{-2}$ (where $r$ is the distance to the cluster center; see, e.g., Rodriguez-Gonzalez et al. 2007).

Cold filaments in SGWs can be formed by the interaction of such SSC winds, provided that the cooling is efficient. Since the gas density of the cluster wind falls with distance, this is likely to happen only when the clusters are very close to each other. The terminal velocity of the SSC winds and their mass-loss rate are also important for determining whether or not we have efficient cooling.

2.2. Radiative Losses in a Cluster Wind

Let us consider a galaxy with a central stellar cluster density $n$ (number of clusters per unit volume). For the sake of simplicity, we consider stellar clusters with identical, isotropic winds, a mass-loss rate $\dot{M}_{\text{w}}$, and a terminal wind velocity $v_{\text{w}}$. The typical separation between stellar clusters is $D \approx n^{-1/3}$.

Therefore, two-wind shock interactions between nearby cluster pairs will occur at a typical distance of $D/2$ from each of the stellar clusters, so that the preshock densities will have values of

$$n_{\text{pre}} = \frac{\dot{M}_{\text{w}}}{1.3 \pi v_{\text{w}} D^2},$$

where $m_H$ is the hydrogen mass and we have assumed a 90% H and 10% He particle abundance.

| $v_{\text{w}}$ (km s$^{-1}$) | $\log_{10}(d_{3,1} \, \text{[pc]})$ |
|---------------------------|------------------|
| $Z_\odot$                 | $5 \, Z_\odot$   | $10 \, Z_\odot$ |
| 100                       | $-1.468$         | $-2.010$         | $-2.283$         |
| 200                       | $-1.194$         | $-1.960$         | $-2.259$         |
| 300                       | $-0.657$         | $-1.439$         | $-1.796$         |
| 400                       | $0.595$          | $-0.991$         | $-0.399$         |
| 500                       | $0.957$          | $0.269$          | $-0.037$         |
| 600                       | $1.176$          | $0.516$          | $0.209$          |
| 700                       | $1.449$          | $0.763$          | $0.455$          |
| 800                       | $1.601$          | $0.913$          | $0.605$          |
| 900                       | $1.727$          | $1.038$          | $0.714$          |
| 1000                      | $1.893$          | $1.208$          | $0.900$          |
| 1100                      | $2.108$          | $1.438$          | $1.123$          |

The shock interactions between nearby clusters will be radiative if the cooling distance $d_{\text{cool}}$ satisfies the condition

$$\kappa \equiv \frac{d_{\text{cool}}}{D} < 1.$$  (2)

In order to estimate the cooling distance, we proceed as follows. Consider the structure that will be formed by the leading shock of a stellar cluster wind with velocity $v_{\text{w}}$ (i.e., the cluster wind velocity) and a preshock density given by equation (1). For a cooling function in the low-density regime, the cooling distance scales as the inverse of the preshock density, yielding

$$d_{\text{cool}}(n_{\text{pre}}, v_{\text{w}}) = \frac{d_{3,1}(v_{\text{w}})}{n_{\text{pre}}}.$$  (3)

where $v_{\text{s}}$ ($=v_{\text{w}}$) is the shock velocity and $d_{3,1}(v_{\text{w}})$ is the cooling distance (to $10^4$ K) behind a shock with $n_{\text{pre}} = 1$ cm$^{-3}$.

We have calculated the function $d_{3,1}(v_{\text{w}})$ by integrating the equations for a one-dimensional, stationary shock (see, e.g., Shull & McKee 1979) using the coronal equilibrium cooling functions for metallicities of 1, 5, and 10 $Z_\odot$ from Raymond et al. (1976). The resulting values of the cooling distance $d_{3,1}(v_{\text{w}})$ (to $10^4$ K, for a $n_{\text{pre}} = 1$ cm$^{-3}$ preshock density) are given in Table 1.

Setting $\kappa = 1$ in equation (2) and using equation (3), one obtains

$$\frac{\dot{M}}{D} = 1.3 m_H \pi v_{\text{w}} d_{3,1}(v_{\text{w}}),$$  (4)

which gives the relation between $\dot{M}/D$ ratio as a function of $v_{\text{w}}$ for SSCs that are just entering the highly radiative regime.

In Figure 1, we plot the $\dot{M}/D$ ratio as a function of $v_{\text{w}}$ for SSCs with $\kappa = 1$ (see eq. [4]) for the three metallicities that we have considered (see above and Table 1). The curves that would be

![Figure 1](image-url)
the wind sources have a radius of positions as described below. For models M1 the cluster winds will be expanding once they leave the galaxy. have chosen is closer to a possible density for the IGM into which and traveled into the intergalactic medium. The density that we sities) before the cluster winds broke out of the galactic plane would be a transient regime (lasting longer for higher ISM den- introduced a higher ISM density (within the galactic plane), there density so that the ISM in the region in between the clusters is of flows in this regime.

radiative shocks in the interactions between nearby stellar clus-

dmental domain was filled initially with a homogeneous, stationary regime, we ran six models. We have assumed that the computa-
highest resolution grid).

ambient medium with a temperature of 92 pc (corresponding to 6 pixels at the maximum grid resolution). We have also computed a fifth simulation, also on a five-level grid resolution) in a domain of 1 kpc (see Table 2). We computed four numerical simulations of SGWs driven with the 3D, adaptive grid code YGUAZU’-A, which is described in detail by Raga et al. (2000, 2002). The first four simulations were performed on a five-level binary adaptive grid with a maximum resolution of 0.488 pc (corresponding to 512 × 512 × 1024 grid points at the maximum grid resolution), in a computational domain of 250 × 250 × 500 pc. We have also computed a fifth simulation, also on a five-level adaptive grid, but with a maximum resolution of 0.976 pc, cor-

ting to 1024 × 1024 × 2048 grid points (at the maximum grid resolution) in a domain of 1 × 2 × 1 kpc (see Table 2).

In order to study the formation of filaments in the radiative regime, we ran six models. We have assumed that the computa-

tional domain was filled initially with a homogenous, stationary ambient medium with a temperature of 1000 K and a density of 0.1 cm^{-3}. This environment clearly does not include the ISM of the disk of a starburst galaxy, for which densities of 1000 cm^{-3} might be more appropriate. We choose this low density so that the ISM in the region in between the clusters is rapidly flushed away by the cluster winds and a stationary wind interaction structure is reached as rapidly as possible. If we in-

troduced a higher ISM density (within the galactic plane), there would be a transient regime (lasting longer for higher ISM densities) before the cluster winds broke out of the galactic plane and traveled into the intergalactic medium. The density that we have chosen is closer to a possible density for the IGM into which the cluster winds will be expanding once they leave the galaxy.

We model the SSCs as spherical wind sources centered at the positions as described below. For models M1–M4 (see Table 2), the wind sources have a radius of R_c = 2.92 pc (corresponding to 6 pixels at the maximum resolution of the adaptive grid, which is always present at the wind sources); for models M2b and M3b, their radius is R_c = 5.84 pc (also corresponding to 6 pixels at the highest resolution grid).

Within these spheres, we impose (at every time step) a wind with a temperature of T_e = 10^7 K, an outwardly directed velocity v_w = 1000 km s^{-1}, and a density that follows an r^{-2} law (where r is the radial coordinate measured outward from the position of each wind source), scaled so as to obtain the correct mass-loss rate. The positions of the wind sources are obtained by sampling a uniform random distribution. However, in practice, we have to modify the obtained cluster distributions in order to avoid the overlap of sources. The stellar cluster sources are placed in a cylindrical structure, which is meant to model the central region of a galactic disk.

### 3.3. The Starburst Regions

In order to reproduce the properties of M82 and NGC 253, we use the average properties reported by Melo et al. (2005) and Melo (2005). For M82, the mean stellar cluster mass (M_{SC}) is 1.7 × 10^{5} M_{\odot}, and the mean separation between neighboring clusters (\Delta) is 12 pc. For NGC 253, M_{SC} = 6.2 × 10^{5} M_{\odot}, and \Delta = 31 pc. We should note that the clusters of Melo et al. (2005) were detected at optical wavelengths. As there is a high level of obscuration in the nuclear regions of M82, as well as in NGC 253, the real number of clusters will be larger and the mean separation between clusters will be smaller than the values quoted above.

We estimate the mass-loss rate \dot{M}_{SC} using the Starburst99 models (Leitherer & Heckman 1995; Leitherer et al. 1999) with the appropriate cluster masses and a Salpeter initial mass function (IMF) including stars between 1 and 100 M_{\odot}. The resulting mass-loss rate (through winds and SNe) is reasonably constant at \geq 4 Myr after the onset of the starburst, with some enhancement when input from SNe overcomes the input from winds. This enhancement occurs at around t \approx 10 Myr and lasts for about 10 Myr, after which the mass-loss rate returns to a value similar to that of the pre-SN phase for another \approx 20 Myr. Finally, the mass-loss rate drops dramatically once the last star of \approx 8 M_{\odot} explodes as a supernova, leaving only winds from intermediate- and low-mass stars (at this point the stellar cluster would no longer be classified as an SSC).

For models M1–M4 we used a constant mass-loss rate with a value consistent with the average mechanical luminosity of the SSCs. However, given the assumptions we have made (of having a system of identical clusters with average properties), a larger mass-loss rate could be possible, especially if the SSCs are in the SN phase. Such a large mass-loss rate could have a significant effect on the production of filaments. For this reason we have run two additional models, M1a and M4a, with extreme values of \dot{M}_{SC} that correspond to upper limits (within the uncertainties), at the peak of the mass-loss rate during the SN phase. Aside from the increased mass-loss rate, these two models are identical to models M1 and M4, respectively (see Table 2).

### 3.2. The Models

We computed four numerical simulations of SGWs driven by stellar clusters, with different metallicities, mass input rates, and numbers of clusters. All of the models were computed with identical stellar clusters with a cluster wind velocity of v_w = 1000 km s^{-1}, placed in a cylinder with a radius of 100 pc and a height of 20 pc. This cylinder represents the central part of the starburst in a galaxy such as M82, with dimensions approaching those of an individual starburst clump (O’Connell et al. 1995; Westmoquette et al. 2007). In reality, the starburst of

### TABLE 2

| Model | Number of SSCs | Z (Z_\odot) | \dot{D} (pc) | M_{SC} (M_\odot yr^{-1}) |
|-------|----------------|------------|-------------|--------------------------|
| M1    | 100            | 1          | 9.27 2 × 10^{-2} | 10^{-1} |
| M1a   | 100            | 1          | 9.27 2 × 10^{-1} | 10^{-1} |
| M2b   | 100            | 5          | 9.27 2 × 10^{-2} | 10^{-1} |
| M3    | 100            | 10         | 9.27 2 × 10^{-2} | 10^{-1} |
| M4    | 15             | 10         | 21.88 4 × 10^{-3} | 10^{-3} |
| M4a   | 15             | 10         | 21.88 4 × 10^{-3} | 10^{-3} |

* The value quoted here is the mean distance between neighboring clusters (nearest neighbors) as measured from the positions that result from sampling a uniform random distribution.

* We have also run models M2b and M3b with the same parameters as models M2 and M3, but with half the spatial resolution and 4 times the spatial extent of models M2 and M3.
M82 has a spatial extent of ~500 pc (see O’Connell & Mangano 1978). Numerical simulations that used the full spatial extent for the cluster distribution would be much more demanding computationally.

From Starburst99, using the mean cluster mass for M82 (Melo 2005), we estimate a mechanical luminosity of $6 \times 10^{59}$ erg s$^{-1}$ per SSC. Using the relation $E_{SC} = M_{SC} v_c^2 / 2$, we find that this luminosity translates into a cluster mass-loss rate of $\sim 2 \times 10^{-2} M_\odot$ yr$^{-1}$. This cluster mass-loss rate has been used in our models M1, M2, and M3. These three models have different metallicities: $Z = 1, 5$, and $10 Z_\odot$ (for models M1, M2, and M3, respectively).

These metallicities have been chosen as representative values of the metallicities of winds from starbursts during the first 20 Myr time evolution. Using the metal yields of Meynet & Maeder (2002), Tenorio-Tagle et al. (2005) have shown that the metallicity of the combined stellar winds remains at a value of $\sim 0.5 Z_\odot$ up to an evolutionary time of $t = 3$ Myr, rapidly grows to $\sim 15 Z_\odot$ at $t \approx 7$ Myr, and then gradually decreases to $\sim 3 Z_\odot$ at $t \approx 20$ Myr.

Similarly, for NGC 253 we obtain a mechanical luminosity of $1.9 \times 10^{59}$ erg s$^{-1}$, which corresponds to a cluster mass-loss rate of $\sim 4 \times 10^{-3} M_\odot$ yr$^{-1}$. This cluster mass-loss rate was used in computing model M4.

For models M1–M3, we have placed 100 clusters within the cylindrical volume described in the beginning of this subsection, which results in a mean separation between clusters of $D = 9.3$ pc, similar to the mean separation of $\Delta = 12$ pc between the clusters of M82 (see § 3.1). Model M4 has a $Z = 10 Z_\odot$ metallicity and has 15 clusters within the cylindrical volume, which results in a mean separation between clusters of $D = 21.9$ pc, similar to the mean separation of $\Delta = 31$ pc between the clusters of NGC 253 (see § 3.1). The parameters of models M1–M4 are summarized in Table 2.

With these parameters, models M2 and M3 lie above the $\kappa = 1$ curves (for the appropriate metallicities), so they are clearly in the highly radiative regime (see Fig. 1). Models M1 and M4 lie below the $\kappa = 1$ curves, so they are not in this regime. Therefore, we would expect dense filaments to form only in models M2 and M3. We evolve models M1, M2, and M3 up to an integration time of $t = 2.5 \times 10^5$ yr, and we evolve model M4 up to $t = 5 \times 10^5$ yr.

In Figure 2, we show the column densities obtained by integrating the number density along the $x$-axis of the domain for the flow stratifications obtained at the end of the time integrations. From this figure, it is clear that models M2 and M3 produce a structure of $\sim 10$–20 filaments both above and below the plane of the galactic disk (within which the SSCs are distributed). Models M1 and M4 do not produce filamentary structures.

The bipolar distribution of the filaments is a direct result of the flattened cylindrical distribution of the SSCs (see Fig. 2). We have also done simulations in which the cylindrical distribution has a height equal to the diameter (not included in the present paper), and they show filamentary structures with an almost isotropic distribution. The same result is, of course, also found for a spherically symmetric cluster distribution.

In Figure 3, we present the column density obtained in the models with extreme mass-loss rates (models M1a and M4a; see Table 2) at $t = 2.5$ and $5 \times 10^5$ yr, respectively. Due to the increase of $M$, the cooling distances become an order of magnitude
shorter (see the density scaling in eq. [3]); thus, the adimensional parameter \( \kappa/C_20 \) for models M1a and M4a is comparable to that of model M3 (\( \kappa < 1 \)). Therefore, as expected, Figure 3 shows filamentary structure, even though it is absent for the same configuration at a lower mass-loss rate.

4. THE GALACTIC WIND EMISSION

4.1. The \( \text{H}_\alpha \) Emission

In Figure 4, we show the \( \text{H}_\alpha \) maps computed by integrating the \( \text{H}_\alpha \) emission coefficient along the x-axis. The emission coefficient is computed with the interpolation formula given by Aller (1987, p. 76) for the temperature dependence of the recombination cascade.

In model M3, we see a structure of \( \text{H}_\alpha \) filaments that extend out from the galactic plane. In model M2 (which has lower radiative losses due to its lower metallicity), the \( \text{H}_\alpha \) filaments appear only at a distance of approximately \( \pm 50 \text{ pc} \) from the galactic plane. Models M1 and M4 do not produce \( \text{H}_\alpha \)-emitting filaments.

The \( \text{H}_\alpha \) filaments in M82 (Ohyama et al. 2002) appear to extend down to the galactic plane, although this effect could partially be due to the fact that the plane of M82 is at an angle of \( \sim 10^\circ \) with respect to the line of sight. We would therefore conclude that the \( Z = 10Z_\odot \) metallicity model M3 appears to be more appropriate for reproducing the \( \text{H}_\alpha \) filaments of M82.

4.2. The X-Ray Emission

We have taken the density and temperature stratifications from the SGW flow configurations and used them to calculate the X-ray emission. We have done this by computing the emission coefficient in the 0.3–2 keV photon energy range using the CHIANTI\(^4\) atomic database and software (see Dere et al. 1997; Landi et al. 2006). For this calculation, it is assumed that the ionization state of the gas corresponds to coronal ionization equilibrium in the low-density regime (i.e., the emission coefficient is proportional to the square of the density).

The X-ray maps corresponding to the end of the time integrations of models M1–M4 are shown in Figure 5. These maps

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\( ^4 \) The CHIANTI database and associated IDL procedures, now distributed as version 5.1, are freely available at http://www.arcetri.astro.it/science/chianti/chianti.html and http://www.damtp.cam.ac.uk/user/astro/chianti/chianti.html.
show that models M1 and M4 (with low radiative losses) produce an extended, diffuse X-ray emission. On the other hand, the highly radiative models M2 and M3 produce X-ray emission that is concentrated to the galactic plane.

M82 shows X-ray emission that extends to large distances (a few kiloparsecs) from the galactic plane (Stevens et al. 2003). Because the preferred model for this galaxy is model M3 (which produces Hα filaments that start from the galactic plane; see Fig. 4 and § 4.1), we see that in order to reconcile the X-ray map predicted from this model (see Fig. 4) and the observed X-ray distribution of M82, we need to assume that the observed X-ray emission comes from another component. This component, for example, could be the shock of the expanding SGW against the intergalactic medium. The emission from this shock is seen in the top and bottom parts of the frames corresponding to models M2 and M3 in Figure 5, but the shock structure is already escaping from the computational domain.

4.3. The Hα Emission at Larger Distances from the Galaxy

Models M1–M4 extend only to 250 pc on either side of the galactic plane. As the filaments in M82 and NGC 1569 extend to ~0.5–1 kpc away from the plane of the galaxy, we have run models M2b and M3b (with the same parameters as models M2 and M3, respectively, but with lower resolutions and larger spatial extents; see § 3 and Table 2) in order to explore whether or not the Hα filaments predicted from our models do extend out to ~1 kpc.

In Figure 6, we show the Hα maps predicted from models M2b (at t = 1.2 × 10^6 yr) and M3b (at t = 1.6 × 10^6 yr). The two times are chosen so as to show an approximate time sequence of the flow, as the two models produce similar results. It is clear that in the two models, the Hα filaments extend to distances of approximately ±500 pc from the galactic plane. In the Hα map of model M3b, there is a transition to a more complex morphology at distances of more than ±300 pc from the galactic plane, which is not seen in model M2b (in which basically the same filaments are seen at larger distances).

5. CONCLUSIONS

We study the formation of filaments in the galactic winds driven by young SSCs in regions of high star formation. We study models in which the filaments are produced solely by the interaction between winds from SSCs, and we do not consider the possible effects of the stratified or clumped ISM present in the galactic disk. In our models, the winds propagate into a low-density, homogeneous environment, which could correspond to the intergalactic medium.

We have shown how the (Mw/D) versus w diagram can be used to determine if the interaction between the winds of SSCs are radiative, in which case cold filaments can be formed. With the (Mw/D) versus w diagram (Fig. 1), one can diagnose whether a galaxy with a high star formation rate will show filaments in optical emission lines, or only a galactic wind with X-ray emission. At the same time, given an observation of a galactic wind with a rich filamentary structure, one could predict the number of SSCs that are contained within the observed galaxy.

We computed three models of dense starbursts (models M1–M3) based on the observed parameters of M82, as well as a fourth model (M4) based on the parameters of NGC 253. The models are based on cluster distributions with mean separations between clusters that are similar to the observed values, but with spatial extents that are considerably smaller than the total extent of the starburst regions. The distributions used in the models could correspond to individual “starburst clumps” such as the ones observed in M82 by Westmoquette et al. (2007).

For the parameters of M82 we computed four models (M1–M3 and M1a) with different metallicities (from solar to 10 times solar). For the parameters of NGC 253 we computed two models (M4 and M4a) with a metallicity of 10 Z⊙. Models M1–M4 assumed a mass-loss rate consistent with the average mechanical luminosity of the SSCs. Models M1a and M4a are obtained with rather extreme mass-loss rates, only achievable during a short-lived phase in which the input from SNe dominates over that from stellar winds.

For the models based on M82, we see the formation of cold, Hα-emitting filaments that extend out from the plane of the galactic disk in the models with metallicities ≤5 Z⊙ (models M2 and M3). We also see formation of dense filaments for the models with extreme mass-loss rates at the supernova phase of the clusters (models M1a and M4a), where a more conservative mass-loss rate did not yield filaments (models M1 and M4).

For the model based on NGC 253 (model M4), no filaments are produced, even for a 10 Z⊙ metallicity. This is consistent with the present observations of this object, in which no Hα-emitting filaments have been detected. The prediction obtained from our models would be that with the distribution of SSCs of NGC 253 (in pre- or post-SN phase), no Hα filaments should exist. However, we have shown that during the SN phase (see model M4a and § 3.1), the formation of cold filaments is possible in such high-metallicity winds. Hoopes et al. (2005) claim that the lack of evidence of filamentary structure in the galactic wind of NGC 253 could simply be the result of not having deep enough Hα maps of this object. In the future we will see whether or not this result is confirmed by deeper observations.

We have also computed X-ray maps in the energy range of 0.3–2 keV. For the highly radiative models (M2 and M3), we find that the X-ray emission is concentrated in a region close to the galactic plane. In order to reconcile this result with the observation of extended X-ray emission in M82, we would have to assume that the emission comes from another component in the flow, which could be the shock of the SGW against the intergalactic medium.
Finally, we have run two models (M2b and M3b) using the parameters based on M82 (and abundances of 5 and 10 $Z_{\odot}$, respectively), with lower computational resolutions but with larger spatial extents. From these runs, we find that the models produce a filamentary Hα morphology that extends out to $\sim 0.5$–1 kpc on each side of the galactic plane.

We end by noting that in this paper, we prove that the radiative interaction between the winds from a disklike distribution of identical SSCs does lead to the production of dense filaments extending out to 100–1000 pc away from the galactic plane. These structures produce Hα emission and might correspond to the filaments observed in starburst galaxies such as M82 and NGC 1569. Of course, in our models we do not consider many elements that are likely to be important in starburst galaxies. Important among these might be the following:

1. the presence of a dense, stratified galactic disk interstellar medium,
2. clumpiness in this medium,
3. the existence of a distribution of sizes and ages for the SSCs, and
4. the effect of galactic mass loading.

There is therefore a large field for future theoretical studies on the formation of filamentary structures in starburst galaxies to explore.

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REFERENCES

Aller, L. H. 1987, Physics of Thermal Gaseous Nebulae (Dordrecht: Reidel)
Anders, P., de Grijs, R., Fritze-v. Alvensleben, U., & Bissantz, N. 2004, MNRAS, 347, 17
Canto, J., Raga, A. C., & Rodriguez, L. F. 2000, ApJ, 536, 896
Chevalier, R. A., & Clegg, A. W. 1985, Nature, 317, 44
Cooper, J. L., Bicknell, G. V., Sutherland, R. S., & Bland-Hawthorn, J. 2008, ApJ, 674, 157
Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, A&AS, 125, 149
Griffiths, R. E., Ptak, A., Feigelson, E. D., Garmire, G., Townsley, L., Brandt, W. N., Sambruna, R., & Bregman, J. N. 2000, Science, 290, 1325
Harris, J., Calzetti, D., Gallagher, J. S., Conselice, C. J., & Smith, D. A. 2001, AJ, 122, 3046
Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
Hoopes, C. G., et al. 2005, ApJ, 619, L99
Landi, E., Del Zanna, G., Young, P. R., Dere, K. P., Mason, H. E., & Landini, M. 2006, ApJS, 162, 261
Leitherer, C., & Heckman, T. M. 1995, ApJS, 96, 9
Leitherer, C., et al. 1999, ApJS, 123, 3
Lynds, C. R., & Sandage, A. R. 1963, ApJ, 137, 1005
Melo, V. P. 2005, Ph.D. thesis, Inst. Astrofıs. Canarias
Melo, V. P., Muñoz-Tuñón, C., Maiz-Apellaniz, J., & Tenorio-Tagle, G. 2005, ApJ, 619, 270
Meynet, G., & Maeder, A. 2002, A&A, 390, 561
O'Connell, R. W., Gallagher, J. S., III, Hunter, D. A., & Colley, W. N. 1995, ApJ, 446, L1
O'Connell, R. W., & Mangano, J. J. 1978, ApJ, 221, 62
Ohyama, Y., et al. 2002, PASJ, 54, 891
Raga, A. C., de Gouveia Dal Pino, E. M., Noriega-Crespo, A., Mininni, P. D., & Velázquez, P. F. 2002, A&A, 392, 267
Raga, A. C., Navarro-González, A., & Villagrán-Muniz, M. 2000, Rev. Mex. AA, 36, 67
Raymond, J. C., Cox, D. P., & Smith, B. W. 1976, ApJ, 204, 290
Rice, W. 1993, AJ, 105, 67
Rodríguez-González, A., Cantó, J., Esquivel, A., Raga, A. C., & Velázquez, P. F. 2007, MNRAS, 380, 1198
Shopbell, P. L., & Bland-Hawthorn, J. 1998, ApJ, 493, 129
Shull, J. M., & McKee, C. F. 1979, ApJ, 227, 131
Stevens, I. R., Read, A. M., & Bravo-Guerrero, J. 2003, MNRAS, 343, L47
Strickland, P. K., & Stevens, I. R. 2000, MNRAS, 314, 511
Tenorio-Tagle, G., Silich, S., & Muñoz-Tuñón, C. 2003, ApJ, 597, 279
Tenorio-Tagle, G., Silich, S., Rodríguez-González, A., & Muñoz-Tuñón, C. 2005, ApJ, 628, L13
Tomisaka, K., & Ikeuchi, S. 1988, ApJ, 330, 695
Westmoquette, M. S., Exter, K. M., Smith, L. J., & Gallagher, J. S., III. 2007, MNRAS, 381, 894
Westmoquette, M. S., Smith, L. J., & Gallagher, J. S., III. 2008, MNRAS, 383, 864