ON THE RAPIDLY COOLING INTERIOR OF SUPERGALACTIC WINDS

S. Silich,1,2 G. Tenorio-Tagle,1 and C. Muñoz-Tuñón3

Received 2002 December 12; accepted 2003 March 2

ABSTRACT

Here we present the steady-state numerical solution and two-dimensional hydrodynamic calculations of supergalactic winds, taking into consideration strong radiative cooling. The two possible outcomes: quasi-adiabatic and strongly radiative flows, are thoroughly discussed, together with their implications on the appearance of supergalactic winds in both the X-ray and visible line regimes.

Subject headings: galaxies: ISM — galaxies: starburst — methods: numerical

1. INTRODUCTION

Massive starbursts, well-localized short episodes of violent star formation, are among the intrinsic characteristics of the evolution of galaxies. They are found at both high and intermediate redshifts (Dawson et al. 2002; Ajiki et al. 2002; Pettini et al. 1998) as well as in galaxies in the local universe (Marlowe et al. 1995; Cairós et al. 2001).

It has usually been assumed that the energy deposition occurs within a region of about 100 pc, the typical size of a starburst. However, recent optical, radio continuum, and IR observations (Ho 1997; Johnson et al. 2001; Gorjian, Turner, & Beck 2001) revealed a number of unusually compact young stellar clusters. These overwhelmingly luminous concentrations of stars present a typical radius of about 3 pc and a mass in the range of $10^4-10^6 M_\odot$. Clearly, these units of star formation (super-star clusters) are very different from what was usually assumed to be a typical starburst, and we shall put a special emphasis on the outflows expected from them.

The large kinetic luminosity produced by violent bursts of star formation is well known to drastically affect the surrounding interstellar medium, generating the giant superbubbles and supershells, detected in a large sample of star-forming galaxies (Bomans 2001). In other cases, the energy input rate is able to drive their associated shock waves to reach the outskirts of their host galaxy, leading, in these cases, to the development of a supergalactic wind with outflow rates of up to several tens of solar masses per year (see Heckman 2001 for a complete review). One of the main implications of such outflows is the clear contamination of the intergalactic medium with the metals recently processed by the massive starburst. In both cases it is usually assumed that at the heart of the starburst, within the region that encompasses the recently formed stellar cluster ($R_{SB}$), the matter ejected by strong stellar winds and supernova explosions is fully thermalized. This generates the large central overpressure responsible for the mechanical luminosity associated with the new starburst. Within the starburst region, it is the mean total mechanical energy $L_{SB}$ and mass $M_{SB}$ deposition rates that 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 Chevalier & Clegg (1985, hereafter CC85) at the boundary $r = R_{SB}$, the thermal and kinetic energy flux amount exactly to $9/20$ and $1/4$ of the total energy flux,

$$\frac{F_{th}}{F_{tot}} = \left(\frac{1}{\gamma - 1} \frac{P}{\rho}\right) \left(\frac{u^2}{\frac{2}{\gamma} + \gamma \frac{P}{\rho}}\right)^{-1} = \frac{9}{20},$$

$$\frac{F_k}{F_{tot}} = \left(\frac{u^2}{\frac{2}{\gamma} + \gamma \frac{P}{\rho}}\right)^{-1} = \frac{1}{4}. \quad (1)$$

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 ($V_\infty \approx 2c_{SB}$). This is due to a fast conversion of thermal energy into kinetic energy in the resultant wind. In this way, as the 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). Previous analyses by Heckman, Armus, & Miley (1990) showed that thermal pressure radial distributions inside superbubble galaxies M82 and NGC 3256 are in a good agreement with the CC85 model. However, Martin, Kobulnicky, & Heckman (2002) found that X-ray surface brightness and radial temperature gradient observed by Chandra in NGC 1569 are inconsistent with CC85 predictions.

Note that the wind is exposed to the appearance of reverse shocks whenever it meets an obstacle cloud or when its thermal pressure becomes lower than that of the surrounding gas, as is the case within superbubbles. There, the high pressure acquired by the swept-up interstellar medium (ISM) becomes larger than that of the freely expanding “free wind region” (FWR), a situation that rapidly leads to the development of a reverse shock, the thermalization of the wind kinetic energy, and to 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 similar to those derived by CC85. Here we study the true physical properties of such well-developed FWRs, taking into consideration strong radiative cooling. Section 2 compares the adiabatic solution of CC85 with our steady-state solution, in which radiative cooling is considered.
§ 2 we also develop an easy criterion to define in which cases radiative cooling is to become dominant. Section 3 displays two-dimensional calculations that use CC85 as the initial condition, which evolves until a new steady state is reached. Section 4 discusses some of the observational consequences of such outflows.

2. THE STEADY-STATE SOLUTION

Following CC85 we assume a spherically symmetric wind, unaffected by the gravitational pull caused by the central star cluster or its associated dark matter component. The equations that govern the steady outflow away from the star-forming region are

\[
\frac{1}{r^2} \frac{d}{dr} (r \mu u^2) = 0, \tag{2}
\]

\[
\rho \frac{du}{dr} = -\frac{dP}{dr}, \tag{3}
\]

\[
\frac{1}{r^2} \frac{d}{dr} \left[ \mu u^2 \left( \frac{\gamma}{2} + \frac{\gamma - 1}{\gamma - 1} \frac{P}{\rho} \right) \right] = -Q, \tag{4}
\]

where \( r \) is the spherical radius and \( u(r), \rho(r), \) and \( P(r) \) are the wind velocity, density, and thermal pressure, respectively. The expression \( Q \) is the cooling rate (\( Q = n^2 A \), where \( n \) is the wind number density and \( A \) is the interstellar cooling function; Raymond, Cox, & Smith 1976). At the boundary of the star cluster (\( R_{SB} \)) we use the solution of CC85,

\[
M_{SB} = (0.1352 \pi \gamma)^{1/2} L_{SB} \frac{S_B}{\sigma_B}, \tag{5}
\]

\[
P = 0.0338 M_{SB}^{1/2} \frac{T_{SB}}{L_{SB}} R_{SB}^2, \tag{6}
\]

\[
T = \frac{0.299 \mu L_{SB}}{k M_{SB}^{1/2}}. \tag{7}
\]

\[
u = c_{SB} = \left( \frac{\gamma k T}{\mu} \right)^{1/2}, \tag{8}
\]

\[
\rho = \frac{M_{SB}}{4 \pi R_{SB}^2 c_{SB}}. \tag{9}
\]

where \( \mu \) is the mean mass per wind particle, \( k \) is the Boltzmann constant, \( \gamma = 5/3 \) is the ratio of specific heats, and \( c_{SB} \) is the sound speed at \( r = R_{SB} \), and then solve equations (2)–(4) numerically. Note that at \( r = R_{SB} \) the wind Mach number \( M_v = 1 \). Therefore, we use the wind velocity as an independent variable at the vicinity of the sonic point. Our numerical solutions for \( Q = 0 \) fully reproduce CC85 adiabatic results.

2.1. Radiative Cooling in Supergalactic Winds

A first order-of-magnitude estimate of whether radiative cooling could affect the thermodynamics of superwinds results from a comparison of the radiative cooling timescale,

\[
\tau_{cool}(r) = \frac{3kT}{nA}, \tag{10}
\]

with the characteristic dynamical timescale,

\[
\tau_{dyn}(r) = \int_r^{R_{SB}} \frac{d\tau}{\rho u(r)}. \tag{11}
\]

The wind density, which, as it streams away, decreases as \((1/r^2)\), in combination with the interstellar cooling curve, fully defines locally the ratio of \( \tau_{cool}/\tau_{dyn} \). One can infer then that if the ratio of the above two quantities becomes smaller than 1, radiative cooling sets in, affecting the thermodynamical properties of the flow. These simple estimates indicate that radiative cooling may become more efficient the more compact a star cluster is. In fact, it is the density of the free wind that really matters. For the same total starburst energy, the more compact a starburst is, the larger the wind density value, and thus the larger the cooling rate. The temperature profiles for a \( 10^{41} \) ergs s\(^{-1}\) starburst with a radius \( R_{SB} = 5 \) pc and different metallicities of the wind material are shown in Figure 1, for both the adiabatic and the radiative cases. Note that for compact starbursts, radiative cooling sets in within a radius \( \leq 10 \) \( R_{SB} \). Despite the rapid drop in temperature, the velocity and the density distributions remain almost unaffected by radiative cooling. In all cases the thermal energy is rapidly transformed into kinetic energy of the wind in the close vicinity of the sonic point. This leads to a fast gas acceleration that allows the wind gas to rapidly approach its terminal velocity \( V_{\infty} \approx 2 c_{SB} \). At the same time, if radiative cooling is considered, the temperature profile strongly deviates away from the adiabatic solution, forcing the gas to soon reach temperature values of the order of \( 10^4 \) K.

One can establish an approximate boundary that separates the adiabatic from the strongly radiative cases, from the condition that \( \tau_{cool} \) becomes equal to \( \tau_{dyn} \). The corresponding curves for different energy input rates, wind terminal velocities, and wind metallicities, as a function of \( R_{SB} \), are shown in Figure 2. If the initial wind parameters \((L_{SB} \text{ and } R_{SB})\) intersect below the corresponding metallicity curve, cooling will be inefficient, and deviations from the adiabatic solution would be negligible. On the other hand, if...
the initial wind parameters intersect above the corresponding metallicity curve, radiative cooling is expected to become important. Note that the larger the wind terminal velocity, the smaller the region of the parameter space covered by the cold wind solution.

3. THE TIME-DEPENDENT SOLUTION

Several two-dimensional calculations using CC85 as the initial condition adiabatic flows have been performed with the Eulerian code described by Tenorio-Tagle & Muñoz Tuñón (1997, 1998). This has been adapted to allow for the continuous injection in the most central zones, of winds with a variety of $L_{\text{SB}}$ and $M_{\text{SB}}$ values. The time-dependent calculations also account for radiative cooling and display the evolution from the adiabatic regime to the more realistic final steady-state solution when radiative cooling is considered. There is an excellent agreement between the time-dependent calculations and the steady-state solutions displayed in §2.

Figure 3 displays isotemperature contours and the velocity field within the central 100 pc$^2$ of a supergalactic wind driven by a $L_{\text{SB}} = 10^{42}$ ergs s$^{-1}$, $c_{\text{SB}} = 500$ km s$^{-1}$, or $V_{\infty} = 1000$ km s$^{-1}$, emanating from a $R_{\text{SB}} = 20$ pc. The solution for $Z = Z_{10}$, as expected from Figure 2, is well into the strongly radiative regime. Figure 3 shows the rapid increase in velocity from its central value to the terminal speed $\sim c_{\text{SB}}$. The top panel shows the run of temperature for the corresponding CC85 adiabatic solution, our initial condition, while the central panels depict how radiative cooling proceeds within the supersonic outflow, leading to the formation of cool parcels of gas ($T \sim 10^4$ K) within rapidly expanding shells of cooling gas. After a few $10^4$ yr a new steady-state solution has been reached (bottom panel). There, the temperature of the fast-moving wind suddenly

![Figure 2](image2.png)

**Fig. 2.**—Adiabatic vs. radiative superwinds. The lines divide the region defined by the parameter space into strongly radiative superwinds (above the lines) and adiabatic solutions (below the lines), for different values of the terminal velocity ($V_{\infty}$) and metallicity.

![Figure 3](image3.png)

**Fig. 3.**—Two-dimensional superwinds. Isotemperature contours, with a separation $\Delta \log T = 0.1$ and the velocity field (longest arrow $= 1000$ km s$^{-1}$) within the central 100 pc$^2$ of a superwind powered by a $10^{42}$ ergs s$^{-1}$ starburst with a radius $R_{\text{SB}} = 20$ pc. The evolution starts from (a) the adiabatic solution of CC85 and continues at (b) $t = 1.3 \times 10^4$, (c) $1.6 \times 10^4$, and (d) $1.9 \times 10^4$ yr when a new steady-state solution is reached. In the bottom panel the gas temperature falls to $10^4$ K before reaching 40 pc from the center. Distance between consecutive tick mark $= 25$ pc in all figures.
plummets from $10^7$ to $10^4$ K at a distance of 37 pc from $R_{SB}$. Cooling takes place in a catastrophic manner, a fact that made us search for possible signs of fragmentation; however, the sudden pressure gradients resulting from cooling are inhibited by the strongly diverging flow, leaving both the density and the velocity fields almost unperturbed. Similar results were obtained when higher metallicity outflows were assumed. The high metallicities are indeed expected from the large inflow of new metals into the superwind (see Silich et al. 2001). Figure 4 shows the final steady-state solution for a wind with $R_{SB} = 5$ pc, $L_{SB} = 10^{41}$ ergs s$^{-1}$, and $V_\infty = 1000$ km s$^{-1}$ when the assumed metallicity of the wind is equal to 1, 3, 5, and 10 $Z_\odot$. Clearly, the impact of this variable is to favor radiative cooling even closer to the $R_{SB}$ surface, a fact that can be also noticed in Figure 1.

4. THE STRUCTURE OF SUPERGALACTIC WINDS

The results from §§ 2 and 3 imply that the structure of supergalactic winds ought to be revised, particularly in the case of powerful sources with a small value of $R_{SB}$, in which radiative cooling reduces the spatial extent of the X-ray-emitting region. In such cases, the only possibility for the origin of an extended hot gas component arises from a shock-heated ISM overrun by the central wind. On the other hand, in lower luminosity and/or widely spread starbursts, the extended hot wind region may also contribute significantly to the total soft X-ray emission. Here we center our attention on very massive and centrally concentrated starbursts, entities that leave no doubt that their newly processed elements will sooner or later be driven into the intergalactic medium. In such cases the central wind is affected by radiative cooling, and the extended structure of such winds will be undetected in the X-ray regime.

Supergalactic winds present a four-zone structure: (1) a central starburst region (a source of hard and soft X-rays); (2) a soft X-ray-emitting zone; (3) the line cooling zone; and (4) a region of recombinant gas, exposed to the UV radiation from the central star cluster.

Figure 5 displays the radial structure of supergalactic winds powered by low-($L_{SB} = 10^{41}$ ergs s$^{-1}$) and high-($L_{SB} = 10^{43}$ ergs s$^{-1}$) luminosity starbursts as a function of $R_{SB}$. In all cases we have assumed a free wind region terminal velocity equal to 1000 km s$^{-1}$ and a $1 Z_\odot$ metal abundance. Solid lines mark the distance at which a $10^{41}$ ergs s$^{-1}$ superwind acquires a temperature of $5 \times 10^5$ and $10^4$ K for an adiabatic solution. Dashed lines present the modified location of the two temperature boundaries provided by gas cooling. Dotted lines mark the position of the two temperature boundaries for energetic starbursts ($10^{43}$ ergs s$^{-1}$). Note that in both the high- and low-luminosity cases we have assumed the same central temperature and thus the same central sound velocity ($c_{SB}$); both cases develop the same terminal speed, leading in the adiabatic regime to the same temperature radial structure. For the low-luminosity radiative cases (heavy dashed lines) significant departures from the adiabatic solution occur for highly concentrated starbursts (say, $R_{SB} \leq 20$ pc) bringing the zone of rapid radiative cooling ($10^4$ K $\leq T \leq 5 \times 10^5$ K) closer to the starburst surface. On the other hand, the radiative solution for the energetic cases (dotted lines) shows how both temperature limits here considered move much closer to the starbursts, reducing significantly the extent of the X-ray and the line-cooling zones. The effect is noticeable for all $R_{SB}$ (from

![Fig. 4.—Metallicity effects. The same as Fig. 3 for a $10^{41}$ ergs s$^{-1}$ superwind with an $R_{SB} = 5$ pc. The panels show the final temperature and velocity distributions for the radiative steady-state solution for (a) $Z = Z_\odot$, (b) $3 Z_\odot$, (c) $5 Z_\odot$, and (d) $10 Z_\odot$.](image)
acquires a temperature of 5 x 10^5 K as a function of the initial radius R_{SB}, for an adiabatic solution. Dashed lines present the modified location of the two temperature boundaries provided by gas cooling (Z = Z^e). Dotted lines mark the position of the two temperature boundaries for energetic starbursts (10^43 erg s^{-1}).

The number of recombinations in the rapidly cooling zone, and the number of recombinations in such a density distribution is, as shown by Franco, Tenorio-Tagle, & Bodenheimer (1990), unable to trap the ionization front. As shown in Figure 5, the size of the X-ray and line-cooling zones become strongly affected by radiative cooling. That is, in the standard approach the predictions and observed superwind X-ray luminosities, which otherwise fit the data reasonably well, cannot reproduce the X-ray luminosities calculated for radiative winds powered by 10^{41} and 10^{43} erg s^{-1} starbursts are presented in Figure 6 as a function of R_{SB}.

4.2. The X-Ray Luminosity

The X-ray luminosity from the hot wind with density distribution n(r) = \frac{M_{w}}{4\pi\mu_{w}u(r)r^2} is

\[ L_X = 4\pi \int_{R_{SB}}^{R_{x}} n^2 \Delta X(T, Z_{w}) r^2 dr, \]

where \Delta X(T, Z_{w}) is the hot-gas X-ray emissivity and R_{x} is the X-ray emission cutoff radius that corresponds to the cutoff temperature T_{cut} \approx 5 \times 10^5 K. This is shown in Figure 5. We then use a model velocity field u(r) and the cutoff radius R_{x} to calculate a wind soft (0.1–2.4 keV) X-ray luminosity. The results of the calculations for L_{w} = 10^{41} and 10^{43} ergs s^{-1} superwinds are shown in Figure 6. We have to conclude that the inconsistency between the free wind model predictions and observed superwind X-ray luminosities, mentioned by Strickland & Stevens (2000), becomes even larger if one takes into account the modifications provided by radiative cooling. That is, in the standard approach the free wind material itself cannot be the main source of diffuse superwind X-ray emission.

5. CONCLUSIONS

We have reanalyzed the physical properties (velocity, density, and temperature) of supergalactic winds powered by a constant energy input rate, taking radiative cooling into account. Three input parameters control the properties of the wind: the total energy input rate L_{SB}, the...
characteristic scale of star formation ($R_{SB}$), and a thermalized gas temperature $T_{SB}$ (or initial wind velocity $c_{SB}$). We have revealed two possible outflow regimes: a hot wind, which due to its low power and low density remains unaffected by cooling, and thus as found by CC85 behaves adiabatically. On the other hand, winds driven by powerful and/or compact starbursts become rapidly dominated by catastrophic radiative cooling.

Superwinds driven by compact and powerful starbursts (see Fig. 2) undergo catastrophic cooling close to their sources and establish a temperature distribution radically different from those obtained in adiabatic calculations. At the same time, both velocity and density radial distributions remain almost unchanged given the speed of the rapidly diverging flow.

The rapid fall in temperature as a function of $r$ reduces the size of the zone radiating in X-rays and decreases the superwind X-ray luminosity. At the same time, cooling brings the $10^4$ K boundary closer to the wind center and promotes the establishment of an extended ionized fast-moving envelope. This should show up as a weak and broad ($\sim$1000 km s$^{-1}$) line-emission component at the base of the much narrower line caused by the central H$\text{ii}$ region.

The authors highly appreciated the friendly hospitality of A. D’Ercole, F. Brighenti, M. Tosi, and F. Matteucci at the superwind 2002 workshop in Bologna, where this study was initiated. They thank the referee for helpful comments and Jeff Wagg for his careful reading of the manuscript. This study has been supported by CONACYT-México, research grant 36132-E, and by the Spanish Consejo Superior de Investigaciones Científicas, grant AYA2001-3939.

REFERENCES

Ajiki, M., et al. 2002, ApJ, 576, L25
Bomans, D. 2001, Rev. Mod. Astron., 14, 297
Brocklehurst, M. 1971, MNRAS, 153, 471
Cairos, L. M., Caon, N., Vilches, J. M., González-Pérez, J. N., & Muñoz-Tuñón, C. 2001, ApJS, 136, 393
Chevalier, R. A., & Clegg, A. W. 1985, Nature, 317, 44
Dawson, S., Spinrad, H., Stern, D., Dey, A., van Breugel, W., de Vries, W., & Reuland, M. 2002, ApJ, 570, 92
Franco, J., Tenorio-Tagle, G., & Bodenheimer, P. 1990, ApJ, 349, 126
Gorjian, V., Turner, J. L., & Beck, S. C. 2001, ApJ, 554, L29
Heckman, T. M. 2001, in ASP Conf. Ser. 240, Gas and Galaxy Evolution, ed. J. E. Hibbard, M. Rupen, & J. H. van Gorkom (San Francisco: ASP), 345
Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
Ho, L. C. 1997, Rev. Mexicana Astron. Astrofís. Ser. Conf., 6, 5

Johnson, K. E., Kobulnicky, H. A., Massy, P., & Conti, P. S. 2001, ApJ, 559, 864
Leitherer, C., & Heckman, T. M. 1995, ApJS, 96, 9
Marlowe, A. T., Heckman, T. M., Wyse, R. F. G., & Schommer, R. 1995, ApJ, 438, 563
Martin, C. L., Kobulnicky, H. A., & Heckman, T. M. 2002, ApJ, 574, 663
Pettini, M., Kellogg, M., Steidel, C., Dickinson, M., Adelberger, K., & Giavalisco, M. 1998, ApJ, 508, 539
Raymond, J. C., Cox, D. P., & Smith, B. W. 1976, ApJ, 204, 290
Silich, S. A., Tenorio-Tagle, G., & Terlevich, E., & Netzer, H. 2001, MNRAS, 324, 191
Strickland, D. K., & Stevens, I. R. 2000, MNRAS, 314, 511
Tenorio-Tagle, G., & Muñoz-Tuñón, C. 1997, ApJ, 478, 134
———. 1998, MNRAS, 293, 299