WINDS DRIVEN BY SUPER STAR CLUSTERS: THE SELF-CONSISTENT RADIATIVE SOLUTION

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ABSTRACT

Here we present a self-consistent stationary solution for spherically symmetric winds driven by massive star clusters under the impact of radiative cooling. We demonstrate that cooling may drastically modify the distribution of temperature if the rate of injected energy approaches a critical value. We also prove that the stationary wind solution does not exist when the energy radiated away at the star cluster center exceeds ~30% of the energy deposition rate. Finally, we thoroughly discuss the expected appearance of super star cluster winds in the X-ray and visible line regimes. The three solutions found, the quasi-adiabatic, the strongly radiative wind, and the inhibited stationary solution, are then compared to the winds from the Arches cluster, the NGC 4303 central cluster, and to the supernebula in NGC 5253.

Subject headings: galaxies: individual (NGC 4303, NGC 5253) — galaxies: star clusters — galaxies: starburst — ISM: kinematics and dynamics — open clusters and associations: individual (Arches)

1. INTRODUCTION

In the stationary solution for spherically symmetric winds (Chevalier & Clegg 1985; hereafter CC85), as well as in the former approach of Holzer & Axford (1970) and in the more recent numerical calculations of Cantó et al. (2000) and Raga et al. (2001), the flow has been assumed to be adiabatic and thus predicts a very extended X-ray envelope around the star cluster surface. However, in none of the above studies were the effects of radiative cooling within the star-forming volume itself taken into consideration.

Here we present a self-consistent semianalytical model of stationary winds driven by massive stellar clusters, taking full account of radiative cooling (see §§ 2 and 3). We first discuss how to find proper wind central values and then use them to integrate numerically the basic equations. We also indicate the threshold value of the energy deposition rate above which a stationary solution is inhibited. In §§ 4 and 5, the three regimes found when radiative cooling is considered, the quasi-adiabatic, the strongly radiative wind, and the inhibited stationary wind, are then compared to well-observed examples. Our conclusions are given in § 6.

2. THE ADIABATIC SOLUTION

Following CC85, Cantó et al. (2000), and Raga et al. (2001), we assume that within a star cluster, within the volume of radius \( R_{sc} \), the matter ejected by stellar winds and supernova explosions is fully thermalized via random interactions. This generates the large central overpressure that continuously accelerates the ejected gas and eventually blows it out of the star cluster volume. There are three star cluster parameters that together define the hydrodynamic properties of the resultant wind outflow (or the run of density, temperature, and expansion velocity, which asymptotically approach \( \rho_w \sim r^{-2}, T_w \sim r^{-4/3}, \) and \( u_w \approx V_{\infty, A} \), respectively). The three parameters are the total energy (\( \dot{E}_{sc} \)) and mass (\( M_{sc} \)) deposition rates and the actual size of the volume that encloses the star cluster (\( R_{sc} \)). The total mass and energy deposition rates also define the wind terminal velocity \( V_{\infty, A} = (2\dot{E}_{sc}/M_{sc})^{1/2} \).

In the adiabatic case there is an analytic solution, and one can thus derive the wind central density, pressure, and temperature (see Cantó et al. 2000) if the above parameters are known,

\[
\rho_c = \frac{M_{sc}}{4\pi B R_{sc}^2 V_{\infty, A}},
\]

\[
P_c = \frac{\gamma - 1}{2\gamma} \frac{M_{sc} V_{\infty, A}}{4\pi B R_{sc}^2},
\]

\[
T_c = \frac{\gamma - 1}{\gamma} \frac{q_c}{k} q_m,
\]

where \( B = [(\gamma - 1)/(\gamma + 1)]^{1/2}[(\gamma + 1)/(6\gamma + 2)]^{(\gamma + 1)/(\gamma + 2)} \), \( q_c \) and \( q_m \) are the energy and mass deposition rates per unit volume (\( q_c = 3\dot{E}_{sc}/4\pi R_{sc}^2 \), \( q_m = 3M_{sc}/4\pi R_{sc}^2 \)), \( \gamma \) is the ratio of specific heats, \( \mu \) is the mean mass per particle, and \( k \) is the Boltzmann constant. Using these initial values, one can solve the stationary wind equations numerically and reproduce the analytic solution throughout the space volume. The relevant equations are

\[
\frac{1}{r^2} \frac{d}{dr} \left( \frac{\rho_w u_w r^2}{2} \right) = q_m,
\]

\[
\rho_w u_w \frac{d}{dr} \left( \frac{u_w}{2} \right) = - \frac{dP_w}{dr} - q_m u_w,
\]

\[
\frac{1}{r^2} \frac{d}{dr} \left[ \rho_w u_w r^2 \left( \frac{u_w^2}{2} + \frac{\gamma P_w}{\gamma - 1} \right) \right] = q_c - Q,
\]

where \( r \) is the spherical radius and \( Q \) is the cooling rate, which is assumed to be equal to zero in CC85, Cantó et al. (2000), and Raga et al. (2001).

Within the central volume, temperature and density present almost homogeneous values whereas the expansion velocity grows almost linearly from 0 km s\(^{-1}\) at the center to the sound...
speed at the cluster radius, \( r = R_{sc} \). There is then a rapid evolution as matter streams away from the star cluster. The flow accelerates rapidly when approaching the sonic point and the wind temperature and density begin to deviate from their central quasi-homogeneous distributions. At large radius, the resultant wind parameters rapidly approach their asymptotic values (see CC85 and Paper I).

3. THE RADIATIVE SOLUTION

Because of the highly nonlinear character of the cooling function, the analytic approach is not valid in the general case that includes radiative cooling, and one thus needs to perform a numerical integration. However, in such a case the star cluster parameters (\( E_{sc}, M_{sc}, \) and \( R_{sc} \)) do not define the wind central temperature and density and the problem arises of how to solve equations (4–6) if neither the initial nor the boundary conditions are known.

To solve the problem, we rewrite equations (4–6) and obtain within the star cluster radius (\( r \leq R_{sc} \))

\[
\frac{du_w}{dr} = \frac{1}{\rho_w} \left( \gamma - 1 \right) (q_c - Q) + q_m \left( \left( \gamma + 1 \right)/2 - c_s^2/3 \right),
\]

and for \( r > R_{sc} \),

\[
\frac{du_w}{dr} = \frac{1}{\rho_w} \left( \gamma - 1 \right) r Q + 2 \gamma u_w P_w,
\]

\[
\frac{dP_w}{dr} = -\frac{M_{sc}}{4 \pi u_w r^2} \frac{du_w}{dr},
\]

\[
\rho_w = \frac{M_{sc}}{4 \pi u_w r^2},
\]

where \( P_w \) is the wind thermal pressure, \( c_s = (\gamma P/\rho)^{1/2} \) is the sound speed, \( Q = n_s^2 \Lambda \), \( n_w \) is the wind atomic number density, and \( \Lambda(Z, T) \) is the cooling function (a function of metallicity and temperature; see Raymond et al. 1976).

It is easy to prove that the derivative of the expansion velocity is positive throughout the space volume only if the sonic point is at the star cluster surface. Indeed, if the expansion velocity becomes supersonic at \( r < R_{sc} \), the right-hand side of equation (7) \( d u_w / dr \) become negative inside the star cluster volume. On the other hand, if the expansion velocity remains subsonic at \( r > R_{sc} \), the right-hand side of equation (10) and the derivative of the expansion velocity become negative outside the star-forming region.

The above implies that a stationary wind solution, which assumes a continuous gas acceleration, exists only if the outflow crosses the star cluster surface at the local sound speed \( u = c_s \) at \( r = R_{sc} \). This conclusion, illustrated in Figure 1, does not depend on the wind thermodynamic properties. It is valid both for the adiabatic (CC85 and Cantó et al. 2000) and for the radiative solution.

There are three possible types of integral curve (Fig. 1) corresponding to different possible positions of the sonic point with respect to the star cluster surface.

1. The stationary wind solution (solid line, \( R_{sonic} = R_{sc} \)). In this case the thermal pressure decreases continually outside the star cluster surface, approaching a negligible value at large radii.

2. The breeze solution (dashed line, \( R_{sonic} > R_{sc} \)). In this case the central temperature \( T_c \) is smaller than in the first case, which shifts the sonic point outside the cluster. This branch of solutions requires of a finite confining pressure and leads to zero velocity at infinity, in agreement with the conclusion of Parker (1958).

3. The unphysical double-valued solution (dotted line, \( R_{sonic} < R_{sc} \)). In this case \( T_c \) is larger than in the stationary wind case. The thermal pressure goes to zero when the expansion velocity approaches the wind terminal speed.

The appropriate solution is selected by the central conditions. In order to obtain a stationary free wind solution, one has to find the wind central density and central temperature that accommodate the sonic point at the star cluster surface \( (u = c_s \) at \( r = R_{sc} \)). This is the key point that allows for the definition of the central \( (r = 0) \) wind parameters and for the numerical solution of equations (7–12).

The wind central temperature \( T_c \) and central atomic number density \( n_c \) are not independent in the radiative case. They are related by the equation

\[
n_c = \frac{q_e - q_m c_s^2 (\gamma - 1) A_{T_c}}{A(T_c)} = q_m \sqrt{\frac{V_{\infty}^2 / 2 - c_s^2 / (\gamma - 1)}{A(T_c)}}.
\]

This results from comparing the derivative of the expansion velocity at the star cluster center, obtained using equation (9), with equation (7). Note that in the absence of radiative cooling, when

\[
Q = n_e^2 \Lambda(T_c) = q_e - q_m c_s^2 = 0,
\]
Equation (13) is transformed into the adiabatic relation (3). Thus, the wind parameters at the star cluster center can be found by iteration of the central temperature until the sonic point takes its proper position at the selected star cluster surface. As in the adiabatic case, \( C_2^6 \) and \( T_c \) are independent and one can always find the central pressure that accommodates the sonic point at the star cluster surface (see eqs. [1] and [3]),

\[
R_{\text{sonic}} = R_{\text{sc}} = \frac{6}{\gamma - 1} \frac{B P_c}{\sqrt{2 q_e q_m}}.
\]

However, this is not the case if radiative cooling is taken into account. In this case, the central density and the central pressure go to zero when the central temperature approaches its maximum value \( T_{\text{max}} = \left[ (\gamma - 1) / \gamma \right] (\mu/k)(q_e/q_m) \) (see eq. [13]). The central pressure increases for smaller values of the central temperature. However, it cannot exceed a maximum value (see eq. [13] and Fig. 2a), which is bound by the gas radiative cooling. At this critical stage the fraction of energy radiated away at the cluster center per unit time, \( \delta = n^2 \Lambda(T_c)/q_e \), reaches \( \approx 30\% \) of the injected energy (see Fig. 2c). If the central temperature becomes even smaller, there is no density enhancement able to compensate for the fall in pressure promoted by radiative cooling. Consequently, the central pressure cannot promote an effective outward acceleration. Therefore, in the radiative case the sonic radius \( R_{\text{sonic}} \) cannot be arbitrarily large and has a maximum value for any given set of star cluster parameters.

**Fig. 2.—**Impact of the central temperature on the outflow. (a) The outflow central pressure; (b) the position of the sonic point; (c) comparison of the deposited and the radiated energies at the star cluster center. In all cases, the energy and the mass deposition rates per unit volume are \( q_e = 2.4 \times 10^{-18} \) ergs cm\(^{-3}\) s\(^{-1}\) and \( q_m = 4.8 \times 10^{-24} \) g cm\(^{-3}\) s\(^{-1}\), respectively. Here \( (2 q_e/q_m)^{3/2} = V_{\infty,d} = 1000 \) km s\(^{-1}\), and the assumed ejected gas metallicity is solar.
Figure 3.—Impact of radiative cooling: the threshold energy input rate above which the stationary wind solution is fully inhibited as a function of the star cluster radius. The solid line represents the threshold energy for star clusters with \((2q_e/q_m)^{1/2} = 1000 \text{ km s}^{-1}\). The dotted and the dashed lines mark the threshold energies for star clusters with \((2q_e/q_m)^{1/2} = 1500\) and \(500 \text{ km s}^{-1}\), respectively.

Figure 4.—Impact of cooling in the extended X-ray zone of stationary winds. Temperature profiles for progressively larger energy deposition rates are shown. Solid, dotted, and dashed lines represent winds with \((0.5, 2, 3) \times 10^{41} \text{ ergs s}^{-1}\), respectively. Here \(R_{\text{sc}} = 10 \text{ pc}\) in all three cases here considered.

The same is true if one moves along the vertical line in Figure 3, from low to high energy input rates. In this case, one is selecting progressively more energetic star clusters within the same volume until the sonic point ends up inside the star cluster (in our example at \(L_{\text{crit}} \approx 4.4 \times 10^{41} \text{ ergs s}^{-1}\)) and the stationary wind solution vanishes.

Once the proper initial conditions are selected, one can solve the main equations (7)–(12) numerically and obtain the wind temperature and density distributions. We have compared, for example, our results with the Stevens & Hartwell (2003) standard model (\(R_{\text{sc}} = 1 \text{ pc}, \dot{M}_{\text{sc}} = 10^{-4} \dot{M}_{\odot} \text{ yr}^{-1}, V_{\infty, d} = 2000 \text{ km s}^{-1}\)). In this case, the stationary wind evolves in the quasi-adiabatic regime and we found an excellent agreement with the Stevens & Hartwell central values and X-ray luminosity. Our model predicts \(T_{\text{c}} = 5.9 \times 10^{7} \text{ K}, n_{e} = 0.65 \text{ cm}^{-3}\), and the X-ray flux between 0.3 and 8.0 keV from the central 1 pc volume \(L_{X} = 5.2 \times 10^{32} \text{ ergs s}^{-1}\).

4. THE EXPECTED APPEARANCE OF STATIONARY RADIATIVE WINDS

Free winds present a four-zone structure (Silich et al. 2003): a star cluster region filled with a hot X-ray plasma, an adjacent X-ray halo with a decreasing temperature distribution, the line-cooling zone, and a region of recombined gas exposed to the UV and soft X-ray radiation from the inner zones and to the UV photons emitted by the star cluster itself.

Figure 4 presents the free-wind temperature distribution for three super star clusters (SSCs), all with the same \(R_{\text{sc}} = 10 \text{ pc}\) radius and the same ratio \((2q_e/q_m)^{1/2} = V_{\infty, d} = 1000 \text{ km s}^{-1}\) but different energy and mass deposition rates. The lowest energy case (solid line) lies well into the adiabatic regime. In the other two cases, however, the radiative cooling clearly modifies the internal wind structure, bringing the boundary of the X-ray zone and the photoionized envelope closer to the star cluster surface. In the most energetic case shown in Figure 4, that for the \(3 \times 10^{41} \text{ ergs s}^{-1}\) star cluster (dashed line), the outer boundary of the X-ray zone \((T_{X} \sim 5 \times 10^{5} \text{ K})\) is a factor of \(\sim 1.5\) smaller than in the adiabatic case. Furthermore, the dimension \(R_{d}\) at which the gas attains a temperature \(\sim 10^{4} \text{ K}\)
lies ~10 times closer to the star cluster center than in the adiabatic case. Consequently, the maximum density of the emission-line envelope is ~10^2 times larger and the emission measure is ~10^3 times larger than in the adiabatic case.

The line-cooling zone and the photoionized envelope may be observed as a broad (~1000 km s^{-1}) emission line component, perhaps of low intensity if compared to the narrow line caused by the central H II region.

It is worth noting that the luminosity of the central H II region decays rapidly after ~3 Myr, when the most massive stars in a coeval cluster begin to move away from the main sequence, whereas the broad component conserves its luminosity by being ionized by the soft X-ray radiation and therefore should be easier to detect in old (>10^7 yr) objects.

The X-ray luminosity of the star cluster wind is given by

\[ L_X = 4\pi \int_0^{R_{\text{sc}}} r^2 n_a^2 \Lambda_X(Z_{\nu}, T_{\nu}) dr, \]

where \( n_a(r) \) is the atomic density distribution, \( R_{\text{sc}} \) is the X-ray cutoff radius where the wind temperature drops below 5 \times 10^5 K, and \( \Lambda_X(Z, T) \) is the X-ray emissivity derived by Raymond & Smith (1977) in their hot-plasma code (see Strickland & Stevens 2000).

5. COMPARISON WITH THE OBSERVATIONS

5.1. The Arches Cluster

The Arches cluster is the densest and the most compact star cluster known in the Local Group. It is located within a ~0.2 pc volume at ~50 pc from the Milky Way center and contains ~120 stars with masses in excess of 20 \( M_\odot \) (Serabyn et al. 1998). The age of the cluster is estimated to be within the range 2–4.5 Myr and the mass is ~10^5 \( M_\odot \) for an initial mass function (IMF) with \( \alpha = 1.6 \) and lower and upper mass cutoffs of 1 and 100 \( M_\odot \), respectively. It was extensively observed in the radio and X-ray regimes (see Lang et al. 2001; Yusef-Zadeh et al. 2002, 2003).

Two sets of calculations for the Arches cluster wind have been presented by Raga et al. (2001) and Stevens & Hartwell (2003). They differ somewhat on the assumed input parameters. Stevens & Hartwell (2003) derived the total mass deposition rate \( M_{\text{sc}} = 7.3 \times 10^{-4} M_\odot \) yr^{-1} and the average individual stellar wind terminal speed \( V_\infty = 2810 \) km s^{-1} from the Lang et al. (1999, 2001) observations of the Arches cluster individual stars and adopted a solar gas metallicity. This set of parameters leads to a total energy deposition rate \( E_{\text{sc}} \approx 1.8 \times 10^{39} \) ergs s^{-1}. Raga et al. (2001) assumed a lower mean individual stellar wind terminal velocity \( V_\infty = 1500 \) km s^{-1} and presented results for a star cluster with 60 identical massive stars, each ejecting \( M_\star = 10^{-4} M_\odot \) yr^{-1}. This implies a total energy input rate \( E_{\text{sc}} \approx 4.2 \times 10^{39} \) ergs s^{-1}. Note that the adiabatic wind X-ray luminosity between 0.3 and 8.0 keV for this set of parameters and \( Z_{\nu} = 2 Z_\odot \) is \( L_X \approx 3 \times 10^{35} \) ergs s^{-1}, approximately 2 orders of magnitude above the value indicated by Raga et al. (2001) \( (L_X \approx 3 \times 10^{35} \) ergs s^{-1}). However, we recover a good agreement with their results if we adopt \( M_\star = 10^{-5} M_\odot \) yr^{-1} instead of the cited value \( M_\star = 10^{-4} M_\odot \) yr^{-1}) for the individual stellar mass-loss rate. This fact indicates a misprint throughout their paper.

The results of the calculations that include radiative cooling for the modified \( (M_\star = 10^{-5} M_\odot \) yr^{-1}) Raga et al. (2001) star cluster model are presented in Figure 5a. For both sets of input parameters (modified Raga et al. 2001 and Stevens & Hartwell 2003), the Arches cluster wind evolves in the quasi-adiabatic regime. For the Raga et al. (2001) star cluster parameters, the central temperature is approximately 3.3 \times 10^5 K. It drops to the X-ray cutoff value (5 \times 10^5 K) at 2.6 pc distance and to 10^4 K at 46.2 pc radius. The calculated 0.3–8.0 keV X-ray luminosity \( L_X = 3 \times 10^{35} \) ergs s^{-1} is in agreement with the Yusef-Zadeh et al. (2002) Chandra data, and the broad emission line luminosities are \( L_{\text{H}\alpha} = 4.9 \times 10^{39} \) ergs s^{-1} and \( L_{\text{Br}\gamma} = 4.7 \times 10^{39} \) ergs s^{-1}. For the Stevens & Hartwell (2003) parameters \( (M_{\text{sc}} = 7.3 \times 10^{-4} M_\odot \) yr^{-1}, \( V_\infty = 2810 \text{ km s}^{-1}) \), the central temperature is \( T_c \approx 1.2 \times 10^4 \text{ K} \), the X-ray cutoff radius is 6.9 pc, and the inner boundary of the photoionized envelope (the 10^4 K radius) is 129 pc. The calculated X-ray luminosity between 0.3 and 8.0 keV and the broad emission line luminosities are \( L_X = 10^{39} \) ergs s^{-1}, \( L_{\text{H}\alpha} = 6.6 \times 10^{34} \) ergs s^{-1}, and \( L_{\text{Br}\gamma} = 6.3 \times 10^{32} \) ergs s^{-1}, respectively.

5.2. The Nucleus of NGC 4303

The galaxy nucleus of NGC 4303 belongs to the class of low-luminosity active galactic nuclei. The energy output rate from the nuclear region is dominated by the compact \( R_{\text{nw}} \approx 1.55 \) pc and massive \( (M_{\text{nw}} \approx 10^5 M_\odot \) SSC. The \( \text{H}\alpha \) luminosity derived from the William Herschel Telescope ISIS \( \text{H}\alpha \) flux corrected for the absorption and aperture effects is 1.2 \times 10^{39} \) ergs s^{-1} (Colina et al. 2002). The SSC ultraviolet spectrum is best fitted by a 4 Myr old instantaneous starburst of 10^5 \( M_\odot \), with a Salpeter IMF and lower and upper stellar mass cutoffs of 1 and 100 \( M_\odot \), respectively. The thermal component of the unresolved core X-ray spectrum is best fitted by \( T \approx 7.5 \times 10^6 \text{ K} \) plasma with the X-ray luminosity between 0.07 and 2.4 keV around 2 \times 10^{18} \) ergs s^{-1} (Jiménez-Bailón et al. 2003).

We adopt a SSC mechanical luminosity, \( L_{\text{sc}} \approx 3 \times 10^{39} \) ergs s^{-1}, predicted by the Leitherer et al. (1999) starburst model, associate the observed hot plasma temperature with the wind central temperature, and derive the wind terminal velocity by iterations from the condition that the flow crosses the star cluster surface with the local sound speed. The calculated wind terminal velocity is 715 km s^{-1}. Figure 5b presents the temperature distribution for this strongly radiative wind and shows how it begins to deviate from the adiabatic profile (solid line) at a distance of ~6 pc away from the center. It falls to the X-ray cutoff value at 5.9 pc and reaches 10^4 K at 31.9 pc. The calculated X-ray luminosity for the 0.3 and 2.0 keV energy range and broad emission line luminosities are \( L_X = 1.3 \times 10^{38} \) ergs s^{-1}, \( L_{\text{H}\alpha} = 1.5 \times 10^{36} \) ergs s^{-1}, and \( L_{\text{Br}\gamma} = 1.4 \times 10^{34} \) ergs s^{-1}, respectively. This implies that the expected \( \text{H}\alpha \) broad luminosity constitutes only 0.1% of the NGC 4303 core \( \text{H}\alpha \) emission.

Figure 5b also demonstrates how the temperature profiles are sensitive to the adopted ejected gas metallicity. In the case of \( Z_{\nu} = 3 Z_\odot \), the X-ray cutoff radius is 5.6 pc, the temperature drops to the 10^4 K value at 14.6 pc, and the calculated wind luminosities are \( L_X = 2.6 \times 10^{35} \) ergs s^{-1}, \( L_{\text{H}\alpha} = 1.3 \times 10^{36} \) ergs s^{-1}, and \( L_{\text{Br}\gamma} = 1.3 \times 10^{34} \) ergs s^{-1}.

5.3. The NGC 5253 Supernebula

NGC 5253 is a nearby (3.8 Mpc) peculiar dwarf galaxy containing numerous massive SSCs (Meurer et al. 1995; Gorjian 1996). An extraordinary compact and bright radio-infrared supernebula has been discovered within the central star-forming region of this galaxy by Turner et al. (2000) and Gorjian et al. (2001). The Lyman continuum rate required
to maintain the ionization of the supernova, \( N_{\text{LyC}} = 4 \times 10^{52} \text{ s}^{-1} \), requires a \((5-7) \times 10^4 \, M_\odot\) star cluster with an energy deposition rate of \( E_{\text{sc}} \approx 2 \times 10^{40} \text{ ergs s}^{-1} \) and a Salpeter mass distribution having 100 and 1 \( M_\odot\) mass cutoff limits (see Leitherer et al. 1999). The mean radius of the ionizing cluster is \( R_{\text{sc}} \approx 0.7 \text{ pc} \). Using the Keck Telescope recombination line spectra, Turner et al. (2003) obtained a recombination line width of 75 km s\(^{-1}\) and concluded that the supernova gas may actually be bound by the gravitational pull of the SSC.

It is worth noting that the above parameters imply that the NGC 5253 SSC is close to our critical energy limit (see Fig. 3) if one assumes that the energy to mass deposition rates ratio is close to \((2q_e/q_m)^{1/2} \sim V_{\infty,A} = 1000 \text{ km s}^{-1}\) (Fig. 3, solid line). If this is the case, a small increase in the ejected gas metallicity (to more than \( Z_w = 1.5 Z_\odot \)) will move the star cluster above the critical value into the forbidden parameter space. This implies that the stationary wind solution may not exist for this particular cluster and that the ejected gas accumulates in the neighborhood of the star cluster. In such a case, the...
supernovae may consist of thermalized matter injected by winds and supernovae that under strong radiative cooling acquires a low sound speed value and is thus unable to stream at high velocities away from the cluster as a stationary wind.

6. CONCLUSIONS

We have developed a self-consistent stationary solution for spherically symmetric winds driven by compact star clusters taking into consideration radiative cooling.

We have shown that stationary radiative winds differ strongly from their adiabatic counterparts. In particular, we have shown that in the energy-size plane there is a regime where the stationary wind solution is inhibited. This occurs whenever the energy radiated away per unit volume and per unit time \([n_e^2 \Lambda(Z_{sw}, T_{sw})]\) surpasses a value of \(~30\%\) of the energy injection rate. In this catastrophic cooling regime, the sonic point cannot be accommodated at the star cluster surface and the stationary wind solution does not exist. Below such a limit the flow, despite radiative cooling, behaves within the star cluster volume in a quasi-adiabatic manner and is able to set the sonic point at the star cluster boundary and evolve into a stationary wind.

Stationary winds driven by stellar clusters with an energy input rate or a size that approaches the critical value establish a temperature distribution radically different from that predicted by the adiabatic solution. In these stationary wind cases, the fast fall of temperature brings the boundaries of the X-ray zone, the line-cooling zone, and the photoionized envelope closer to the star cluster center. This promotes the establishment of a compact ionized gaseous envelope that should be detected as a weak and broad (~1000 km s\(^{-1}\)) emission line component at the base of a much narrower line caused by the central H \(\Pi\) region.

Note that the threshold energy input rate approaches an asymptotic value for large values of \(R_{sc}\) (see Fig. 3). This implies that single supermassive star clusters are not able to generate stationary outflows whatever their radii may be. The fate of the ejected material in this case remains unclear. A self-regulating star-forming region may form and may keep the injected gas bound because of catastrophic radiative cooling or the gas may be blown away in a quasi-recurrent regime. The outflows driven by supermassive or supercompact star clusters should be studied with a full nonstationary hydrodynamic approach.

We have speculated that the supernovae in NGC 5253 seems a good example of this inhibited stationary wind regime. Radiative cooling enforces a rapid drop in the sound speed value and the injected matter remains near the cluster. In such a case, we predict that the metallicity of the supernovae is above solar, making the cluster lie above the threshold limit for stationary winds (Figs. 3 and 5).

Our calculations show that the Arches cluster wind seems to evolve in the quasi-adiabatic regime and predicts the \(H_\alpha\) and \(Br\gamma\) broad component luminosities around \(L_{H\alpha} \approx 5 \times 10^{34}\) ergs s\(^{-1}\) and \(L_{Br\gamma} \approx 5 \times 10^{32}\) ergs s\(^{-1}\), respectively.

The temperature distribution derived for the NGC 4303 central 1.55 pc star cluster wind is radically different from the adiabatic temperature distribution even for a solar metallicity. The calculated X-ray luminosity is in reasonable agreement with the observed diffuse component luminosity. The radiative model also predicts a compact (between 6 pc and 30 pc) broad-line emission with \(L_{H\alpha} \approx 10^{36}\) ergs s\(^{-1}\) and \(L_{Br\gamma} \approx 10^{34}\) ergs s\(^{-1}\).

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