WINDS DRIVEN BY MASSIVE STAR CLUSTERS

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Abstract

Here I discuss the X-ray emission resulting from the interaction of star cluster winds with the surrounding medium. I demonstrate that X-ray emission from the free wind region dominates the total bubble X-ray luminosity if the central star cluster is sufficiently young, massive and compact. I also prove that strong radiative cooling is a crucial ingredient which defines the physical properties and observational manifestations of gaseous outflows generated within such clusters. It may modify drastically the distribution of temperature if the rate of injected energy approaches a critical value. I also show that the stationary wind solution does not exist whenever the energy radiated away at the star cluster center exceeds $\sim$ 30% of the energy deposition rate. This implies that stationary star cluster winds may evolve either in the quasi-adiabatic or in the strongly radiative regimes. I then compare our model to the winds from Arches cluster and NGC4303 central cluster and demonstrate that Arches cluster wind evolves in a quasi-adiabatic regime whereas the NGC4303 cluster wind seems to be strongly affected by the radiative cooling.

1 Introduction

Young massive stars are found to be concentrated into star clusters of different masses and sizes. The combined power of strong stellar winds and supernovae explosions within such clusters produce outflows of ejected material which is known as the star cluster winds.

Star cluster winds interact with the surrounding medium generating strong shocks which collect interstellar gas and result in expanding shells moving outward from the star cluster centers. The resulting structures are known as interstellar bubbles and consist of four distinct zones depicted in Fig. 1 (see Weaver et al. 1977; Bisnovatyi-Kogan & Silich 1995 and references therein). The central free supersonic ejecta (zone A), a region of shocked, heated by the reverse shock, ejecta (zone B), a cold outer shell (zone C) separated from the shocked ejecta by the contact discontinuity, and from the surrounding interstellar medium (zone D) by the outer shock front.

The density and the temperature distributions within zone B are defined by the thermal evaporation of the cold shell material. They are (Weaver et al. 1977; Mac Low & McCray 1988):

$$n(r) = n_c(1 - r/R_s)^{-2/5}, \quad (1)$$

$$T(r) = T_c(1 - r/R_s)^{2/5}, \quad (2)$$

where r is the distance from the bubble center, R_s is the shell radius, and n_c and T_c are the central density and the central temperature, respectively. Both, n_c and T_c, are functions of time. The X-ray emission of interstellar bubbles is usually associated with the shocked hot ejecta (zone B) diluted by the interstellar gas evaporated from the cold outer shell. Assuming that X-ray emissivity, Λ_x, does not depend on temperature, Chu et al. (1995) obtained:

$$L_{x,bubble} = 10^{36} I(\tau) L_{38}^{33/35} n_{ISM}^{17/35} t_7^{19/35} ergs^{-1}, \quad (3)$$

where L_{38} is the star cluster mechanical luminosity in 10^{38} erg s^{-1} units, n_{ISM} is the interstellar medium (ISM) number density, t_7 is the evolutionary time in 10^7 yr units, and

$$I(\tau) = \frac{125}{33} - 5\tau^{1/2} + \frac{5}{3}\tau^3 - \frac{5}{11}\tau^{11/2}. \quad (4)$$

$\tau = T_{cut}/T_c$ is the ratio of the X-ray cut-off temperature ($T_{cut} \approx 5\times10^5$ K) to the bubble central temperature T_c.

The X-ray luminosity from the star cluster wind (zone A) is not usually taken into account (Chu et al. 1995),

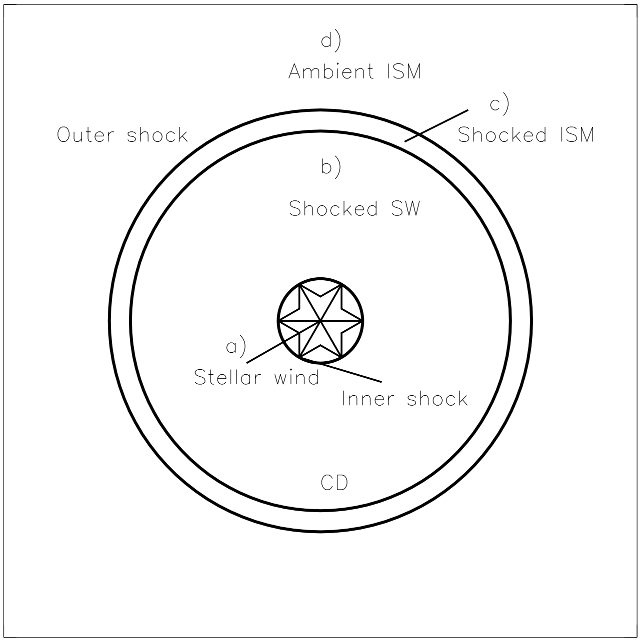

Figure 1: The schematic representation of the interstellar bubble structure.

or it is calculated separately and is not compared with the bubble (zone B) luminosity (Raga et al. 2001; Stevens & Hartwell 2003). Meanwhile, the relative contributions of zone B and zone A to the total bubble X-ray luminosity is dependent on the star cluster parameters, the ISM density, and the evolutionary time t (or bubble radius R_s). Indeed, approximating the adiabatic wind density and temperature profiles (see discussion below) by constant values inside the star cluster radius R_{sc}, and by $n(r) \sim r^{-2}$ and $T(r) \sim r^{-4/3}$ functions outside of R_{sc}, and adopting Chu et al. (1995) approximation for the X-ray emissivity Λ_x, one can obtain for the star cluster wind luminosity

$$L_{x,wind} = \frac{2.5 \times 10^{35} L_{38}^2}{R_{sc,1} V_{w,1000}^6} \left[11 - \frac{3}{4}\frac{R_{sc}}{R_x}\right] ergs^{-1}, \quad (5)$$

where $R_{sc,1}$ and $V_{w,1000}$ are the star cluster wind radius and terminal velocity in 1 pc and 1000 km s^{-1} units, respectively, and R_x is the cut-off radius for the wind X-ray emission. R_x equals either to the reverse shock radius, R_{RS}, or to the radius where the wind temperature drops to the X-ray cut-off value. The maximum possible X-ray luminosity of the wind is:

$$L_{xmax,wind} = \frac{2.5 \times 10^{35} L_{38}^2}{R_{sc,1} V_{w,1000}^6} ergs^{-1}. \quad (6)$$

X-ray emission from zone A dominates the total bubble X-ray luminosity until the evolutionary time t remains smaller than

$$t_{crit} = \left[\frac{0.25}{I(\tau)}\right]^{35/19} \frac{L_{38}^{37/19}}{R_{sc,1}^{35/19} n_{ISM}^{33/19} V_{w,1000}^{210/19}} 10^7 yr. \quad (7)$$

In the following sections I will concentrate on the star cluster wind properties. This implies that in my later discussion I assume that star clusters are sufficiently young, massive and compact. This discussion is based on the Silich et al. (2004) results.

2 The stationary wind solution

The prototype star cluster wind model was proposed by Chevalier and Clegg (1985). Their concept includes three basic assumptions: all energy deposited by massive stars inside a star cluster is completely thermalized via random collisions of individual stellar winds and young supernova remnants. This generates the large central overpressure which accelerates the ejected material and forms the massive gaseous outflow; the outflow is stationary and adiabatic. In this approach three parameters completely define a star cluster free wind expansion. They are the energy L_w and the mass $\dot{M}_w$ deposition rates, and the star cluster radius R_{sc}. The adiabatic solution predicts a specific internal wind structure with very extended, hot, X-ray emitting gaseous envelope around the central cluster.

More recent numerical and semi-analytical calculations of Cantó et al. (2000), Raga et al. (2001), Stevens & Hartwell (2003) incorporated the individual stellar wind collisions and an additional mass loading, however kept the adiabatic assumption untouched.

The impact of cooling on the stationary wind solution, was discussed by Silich et al. (2003) for winds driven by powerful and compact stellar clusters, and by Wang (1995) for gas outflows from galaxies. However, the above studies remained inconsistent because did not consider the impact of cooling inside the star cluster volume. The self-consistent model taking into consideration the effects of radiative cooling within the star cluster volume was proposed by Silich et al. (2004) and is presented here.

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

$$\rho_c = \frac{\dot{M}_{sc}}{4\pi B R_{sc}^2 V_{\infty A}}, \tag{8}$$

$$P_c = \frac{\gamma - 1}{2\gamma} \frac{\dot{M}_{sc} V_{\infty A}}{4\pi B R_{sc}^2}, \tag{9}$$

$$T_c = \frac{\gamma - 1}{\gamma} \frac{\mu}{k} \frac{q_e}{q_m}, \tag{10}$$

where $V_{\infty A} = \sqrt{2L_{sc}/\dot{M}_{sc}}$ is the adiabatic wind terminal speed, $B = \left(\frac{\gamma-1}{\gamma+1}\right)^{1/2} \left(\frac{\gamma+1}{6\gamma+2}\right)^{(3\gamma+1)/(5\gamma+1)}$, q_e and q_m are the energy and mass deposition rates per unit volume ($q_e = 3L_{sc}/4\pi R_{sc}^3$; $q_m = 3\dot{M}_{sc}/4\pi R_{sc}^3$), γ is the ratio of specific heats, μ 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. Within the star cluster radius R_{sc}, 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 $r = R_{sc}$. 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 $V_w \to V_\infty$, $\rho_w \sim r^{-2}$, $T_w \sim r^{-4/3}$.

Due to the highly nonlinear character of the cooling function, the analytic approach is not valid in the general case that includes radiative cooling, and thus one needs to perform a numerical integration. However in such a case, the star cluster parameters (L_{sc}, $\dot{M}_{sc}$ and R_{sc}) do not define the wind central temperature and density and the problem arises: how to solve the stationary hydrodynamic equations if neither the initial nor the boundary conditions are known?

To solve the problem we re-write the main Eq. and obtain within the star cluster radius ($r \le R_{sc}$)

$$\frac{\mathrm{d}u_w}{\mathrm{d}r} = \frac{1}{\rho_w} \frac{(\gamma - 1)(q_e - Q) + q_m(\frac{\gamma+1}{2}u_w^2 - \frac{2}{3}c_s^2)}{c_s^2 - u_w^2}, \tag{11}$$

$$\frac{\mathrm{d}P_w}{\mathrm{d}r} = -q_m \left(\frac{r}{3}\frac{\mathrm{d}u_w}{\mathrm{d}r} + u_w\right), \tag{12}$$

$$\rho_w = \frac{q_m r}{3u_w}, \tag{13}$$

and for $r > R_{sc}$

$$\frac{\mathrm{d}u_w}{\mathrm{d}r} = \frac{1}{\rho_w} \frac{(\gamma - 1)rQ + 2\gamma u_w P_w}{r(u_w^2 - c_s^2)}, \tag{14}$$

$$\frac{\mathrm{d}P_w}{\mathrm{d}r} = -\frac{\dot{M}_{sc}}{4\pi r^2} \frac{\mathrm{d}u_w}{\mathrm{d}r}, \tag{15}$$

$$\rho_w = \frac{\dot{M}_{sc}}{4\pi u_w r^2}. \tag{16}$$

In Eq. (11-13) P_w is the wind thermal pressure, $c_s = (\gamma P/\rho)^{1/2}$ is the sound speed, $Q = n_w^2 \Lambda$ is the cooling rate, n_w is the wind atomic number density and $\Lambda(Z, T)$ is the cooling function.

It is easy to prove that the derivative of the expansion velocity is positive throughout the space volume, only if the sonic point lies at the star cluster surface. 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 $r = R_{sc}$). Otherwise one gets either a breeze solution with zero expansion velocity at infinity, or an unphysical double valued solution (see Silich et al. 2004).

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 which accommodate the sonic point at the star cluster surface ($u = c_s$ at $r = R_{sc}$).

In the adiabatic case

$$R_{sonic} = R_{sc} = \frac{6\gamma}{\gamma - 1} \frac{BP_c}{\sqrt{2q_e q_m}}, \tag{17}$$

the wind central density ρ_c and temperature T_c are independent, and therefore one can always find the central pressure which accommodates sonic point at the star cluster surface.

In the radiative case the wind central temperature T_c and central density are not independent. Therefore the central pressure P_c cannot exceed a maximum value bound by the gas radiative cooling and the sonic radius, R_{sonic}, cannot be arbitrarily large for any set of star cluster parameters. This implies that within some parameter space the stationary wind solution does not exist. This conclusion is stressed in Fig. 2. Moving from right to left along the horizontal line is equivalent to considering progressively more compact clusters, all

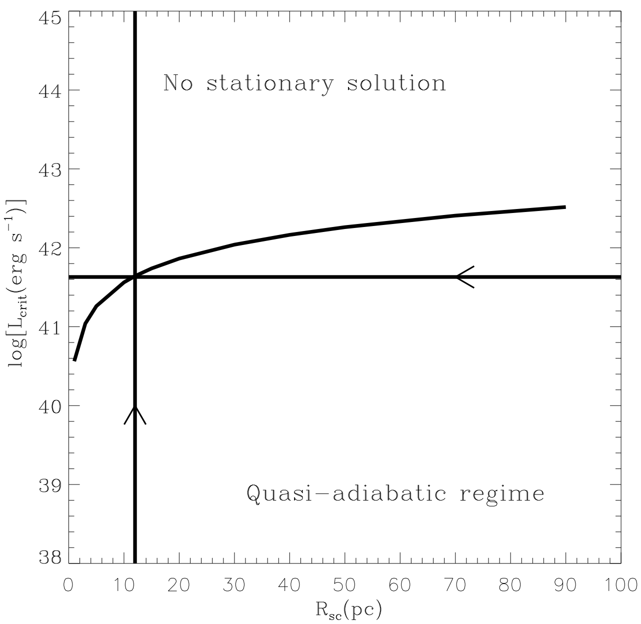

Figure 2: The impact of radiative cooling. The threshold energy input rate above which the stationary wind solution is fully inhibited, as function of the star cluster radius. $(2q_e/q_m)^{1/2} = V_{\infty A}$ = 1000 km s^{-1}.

with the same energy and mass deposition rates ($L_{sc} \approx 4.4\times10^{41}$ erg s^{-1}; $\dot{M}_{sc} \approx 1.4$ $M_\odot$ yr^{-1}). For large star clusters the maximum allowed sonic radius R_{sonic} exceeds the star cluster radius R_{sc}, however one can accommodate the sonic point at the star cluster surface once a proper central temperature is selected and obtain a stationary wind solution. However, if the considered star cluster is smaller than the critical value ($\sim$ 12 pc for the example shown in Fig. 2), the maximum allowed sonic point radius moves inside the star cluster and the stationary wind solution vanishes.

The same is true if one moves along the vertical line in Fig. 2, 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 $L_{crit} \approx 4.4\times10^{41}$ erg s^{-1}) and the stationary wind solution vanishes.

Once the proper initial conditions are selected, one can solve the main Eq. (11-16) numerically and obtain the wind temperature and density distributions. We have compared our results with Stevens & Hartwell (2003) standard model (R_{sc} = 1 pc, $\dot{M}_{sc} = 10^{-4}$ $M_\odot$ yr^{-1}, $V_{\infty A}$ = 2000 km s^{-1}). In this case the stationary wind evolves in the quasi-adiabatic regime and we found an excellent agreement with Stevens & Hartwell central values and X-ray luminosity. Our model predicts T_c = 5.9$\times10^7$ K, n_c = 0.65 cm^{-3} and the X-ray flux between 0.3 and 8.0 keV from the central 1 pc volume L_x = 5.2$\times10^{32}$ erg s^{-1}.

3 The individual super-star clusters

In this section I apply our method to well known super-star clusters: the Arches cluster and NGC4303 central cluster.

3.1 The Arches cluster

The Arches cluster is the densest and the most compact star cluster known in the Local Group. It contains $\sim$ 120 stars with masses in excess of 20 $M_\odot$ (Serabyn et al. 1998) and has been extensively observed in the IR, radio and X-ray regimes (see Lang et al. 2001; Yusef-Zadeh et al. 2002, 2003). The mass of the cluster is $\sim 10^4$ $M_\odot$.

Two sets of adiabatic 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 $\dot{M}_{sc}$ = 7.3$\times10^{-4}$ $M_\odot$ yr^{-1} and the average individual stellar wind terminal speed V_∞ = 2810 km s^{-1} from Lang et al. (1999) observations and adopted a Solar gas metallicity. Raga et al. (2001) assumed a lower mean individual stellar wind terminal velocity (V_∞ = 1500 km s^{-1}) and presented results for a star cluster with 60 identical massive stars and twice Solar abundances of heavy elements.

Our results are presented in Fig. 3a. For both sets of input parameters the Arches cluster wind evolves in the quasi-adiabatic regime. The calculated X-ray luminosity between 0.3 and 8.0 keV L_x = (1-3)$\times10^{35}$ erg s^{-1} is in agreement with Yusef-Zadeh et al. (2002) *Chandra* data and Raga et al. (2001) calculations. In this respect it is worth noticing a misprint in the original Raga et al. 2001 paper where the calculated X-ray luminosity of the Arches cluster wind ($L_{x,wind} \sim 3\times10^{35}$ erg s^{-1}) implies the individual stellar wind mass loss rate $\dot{M}_\star \approx 10^{-5}$ $M_\odot$ yr^{-1}. The mass loss rate from individual stars which is indicated in the paper ($\dot{M}_\star = 10^{-4}$ $M_\odot$ yr^{-1}) leads, in agreement with our Eq. (5), to the two orders of magnitude larger X-ray luminosity. The expected broad emission line luminosities are around $L_{H\alpha}$ = 5$\times10^{34}$ erg s^{-1} and $L_{Br\gamma}$ = 5$\times10^{32}$ erg s^{-1}, respectively.

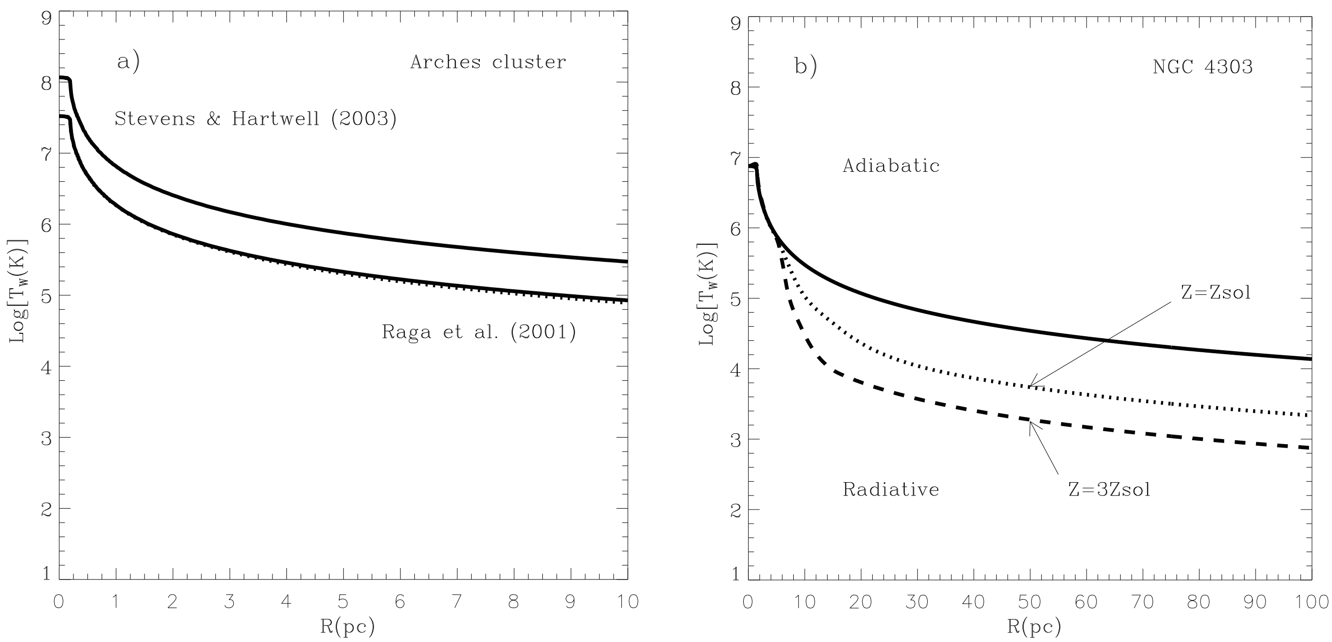

Figure 3: The stationary wind temperature distributions. a) The quasi-adiabatic wind from the Arches cluster. The radiative solution is shown by dotted lines. b) The strongly radiative wind from the NGC4303 nuclear super-star cluster. The adiabatic temperature distribution is shown by the solid line.

3.2 The nucleus of NGC4303

The energy output from the nuclear region of NGC4303 galaxy is dominated by the compact (R_{sc} $\approx$ 1.55 pc) and massive ($M_{sc} \approx 10^5$ $M_{\odot}$) super-star cluster (Colina et al. 2002). The thermal component of the unresolved-core X-ray spectrum is best fitted by T $\approx$ a 7.5×10^6 K plasma with the X-ray luminosity between 0.07 keV and 2.4 keV around 2×10^{38} erg s^{-1} (Jiménez-Bailón et al. 2003).

For the calculations we adopt a synchrotron self-Compton mechanical luminosity, $L_{sc} \approx 3\times10^{39}$ erg s^{-1}, derived from the Leitherer et al. (1999) starburst model and associate the observed hot plasma temperature with the wind central temperature. The results of the calculations are presented in Fig. 3b. The star cluster wind evolves in a strongly radiative regime. The temperature distribution begins to deviate from the adiabatic profile (solid line) at a distance $\sim$ 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 0.3 and 2.0 keV energy range and broad emission line luminosities are L_x = 1.3×10^{38} erg s^{-1}, $L_{H\alpha}$ = 1.5×10^{36} erg s^{-1} and $L_{Br\gamma}$ = 1.4×10^{34} erg s^{-1}, respectively. This implies that the expected Hα broad luminosity constitutes about 0.1% of the NGC4303 core Hα emission.

4 Conclusions

X-ray emission from the free wind region dominates the total bubble X-ray luminosity if the central star cluster is sufficiently young, massive and compact.

Strong radiative cooling is a crucial ingredient which defines the physical properties and observational manifestations of the gaseous outflows from massive and compact super-star clusters. It modifies drastically the outflow temperature distribution bringing 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 which should be detected as a week and broad ($\sim$ 1000 km s^{-1}) emission line component at the base of a much narrower line caused by the central H II region.

The impact of radiative cooling becomes progressively more important for star clusters with larger masses and smaller radii. In particular we have found the energy input limit above which the stationary wind solution is inhibited. The star cluster wind evolves in the quasi-adiabatic regime when energy deposited by individual stellar winds and supernovae explosions is well below the critical value. Stationary winds driven by stellar clusters with energy input rates that approach the critical value, establish a temperature distribution with a fast temperature drop close to the star cluster surface, radically different from that predicted by the adiabatic solution. The stationary wind solution vanishes if the energy input rate exceeds the critical value.

Our numerical calculations confirm that the Arches cluster wind evolves in a quasi-adiabatic regime. The NGC4303 cluster wind is found to be strongly affected by the radiative cooling.

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