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WINDS DRIVEN BY SUPER-STAR CLUSTERS

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RESUMEN

Presentamos la solución estacionaria auto-consistente para vientos esfericamente simétricos empujados por cúmulos masivos de estrellas considerando el impacto del enfriamiento radiativo. Demostramos que el enfriamiento puede modificar drásticamente la distribución de temperatura si latasa de inyección de energía se aproxima a un valor crítico y que la solución de viento estacionario no existe si la deposición de energía excede este límite. Finalmente, discutimos la apariencia esperada de supervientos galácticos impulsados por múltiples supercúmulos estelares.

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 modify drastically the distribution of temperature if the rate of injected energy approaches a critical value and that the stationary wind solution does not exist if the energy deposition rate exceeds this limit. Finally, we discuss the expected appearance of the supergalactic winds driven by multiple super-star clusters.

Key Words: **GALAXIES: STAR CLUSTERS — STARS: WINDS, OUTFLOWS**

1. THE CONCEPT OF THE STAR CLUSTER WIND

The model for star cluster winds was first proposed by Chevalier and Clegg (1985; hereafter referred to as CC85). Their model is based on several simplifications: the outflow is assumed to be adiabatic, stationary and spherically symmetric. The gravitational pull from the star cluster is negligible and all deposited energy is thermalized within a star forming region via individual stellar winds and supernova remnants random collisions. This generates the large central overpressure that accelerates the ejected material and blows it out of the star forming volume with a supersonic terminal speed.

Several modifications have been included over the years. Cantó et al. (2000) confirmed CC85 results by means of 3D adiabatic numerical calculations, Stevens & Hartwell (2003) discussed effects of additional mass-loading ant the impact of cooling on the stationary wind solution was discussed by Wang (1995) and Silich et al. (2003). However, in all of the above studies, the effects of radiative cooling within the star forming volume itself were not taken into account.

In this presentation we develop a self-consistent radiative model for stationary winds driven by massive stellar clusters taking into consideration radiative cooling throughout the space volume, including the star forming region itself.

2. THE STATIONARY WIND SOLUTION

In the adiabatic solution there are three star cluster parameters which together completely define the hydrodynamical properties of the resultant wind outflow (the run of density, temperature and expansion velocity). These are: the total energy ($\dot{E}_{sc}$) and mass ($\dot{M}_{sc}$) 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 adiabatic wind terminal velocity $V_{\infty A} = \sqrt{2\dot{E}_{sc}/\dot{M}_{sc}}$.

2.1. *The adiabatic solution*

In the adiabatic case there is an analytic solution (CC85). The central wind density, pressure and temperature are:

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

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

$$T_c = \frac{\gamma - 1}{\gamma}\frac{\mu}{k}\frac{q_e}{q_m}, \tag{3}$$

where $B = \left(\frac{\gamma-1}{\gamma+1}\right)^{1/2}\left(\frac{\gamma+1}{6\gamma+2}\right)^{(3\gamma+1)/(5\gamma+1)}$, q_e and q_m are the energy and mass deposition rates per

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unit volume ($q_e = 3\dot{E}_{sc}/4\pi R_{sc}^3$; $q_m = 3\dot{M}_{sc}/4\pi R_{sc}^3$), 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.

At large distance ($r \gg R_{sc}$), the wind parameters approach their asymptotic values: $\rho_w \sim r^{-2}$, $T_w \sim r^{-4/3}$ $u_w \approx V_{\infty A}$.

2.2. *The radiative solution*

In the radiative case the highly nonlinear character of the cooling function inhibits the analytic approach and one has to integrate the basic equations numerically. However in such a case, the star cluster parameters ($\dot{E}_{sc}$, $\dot{M}_{sc}$ and R_{sc}) do not define the wind central temperature and density and the problem arises: how to solve main equations numerically if neither the initial nor the boundary conditions are known?

To overcome this problem one has to realize that in general case there are three possible types of integral curve (see Figure 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 continuously 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 T_c is smaller than in the first case. This branch of solutions requires of a finite confining pressure and leads to zero velocity at infinity. 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 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 doesn't depend on the wind thermodynamic properties. It is valid both for the adiabatic (CC85 and Cantó et al. 2000) and for the radiative solution.

The appropriate solution is selected by the central conditions. In order to obtain a stationary wind solution, one has to find the wind central density and temperature which accommodate the sonic point at the star cluster surface ($u = c_s$ at $r = R_{sc}$). The wind central temperature T_c and density n_c are not independent in the radiative case. They are related

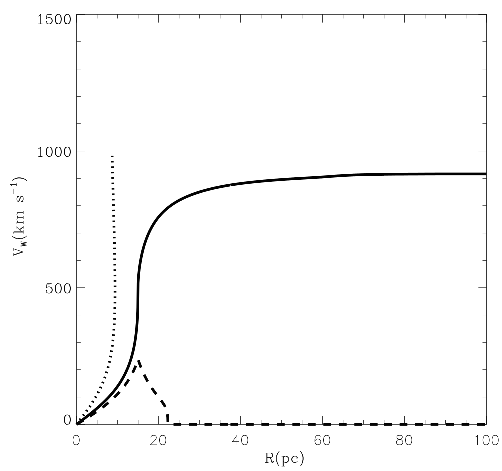

Fig. 1. Three possible types of integral curves. 1) The stationary wind solution (solid line), $R_{sonic} = R_{sc}$. 2) The breeze solution (dashed line), $R_{sonic} > R_{sc}$. 3) Unphysical double valued solution (dotted line), $R_{sonic} < R_{sc}$. For the three examples we adopted $\dot{E}_{sc} = 10^{41}$ erg s^{-1}, $R_{sc} = 15$ pc, $V_{\infty A} = (2q_e/q_m)^{1/2} = 1000$ km s^{-1}.

by the equation

$$n_c = \sqrt{\frac{q_e - \frac{q_m}{\gamma-1}c_c^2}{\Lambda(T_c)}} = q_m^{1/2}\sqrt{\frac{\frac{V_{\infty A}^2}{2} - \frac{c_c^2}{\gamma-1}}{\Lambda(T_c)}}, \qquad (4)$$

where $\Lambda(T)$ is the cooling function. 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.

3. THE THRESHOLD ENERGY INPUT RATE

In the adiabatic case ρ_c and T_c are independent and one can always find the central pressure that accommodates the sonic point at the star cluster surface:

$$R_{sonic} = R_{sc} = \frac{6\gamma}{\gamma - 1}\frac{BP_c}{\sqrt{2q_e q_m}}. \qquad (5)$$

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 $T_{max} = \frac{\gamma-1}{\gamma}\frac{\mu}{k}\frac{q_e}{q_m}$. P_c increases for smaller values of the central temperature. However, it cannot exceed a maximum value bound by the gas radiative cooling. At this critical stage the fraction of energy radiated away at the cluster center per unit time, $\delta = (q_e - n_c^2\Lambda(T_c))/q_e$, reaches $\approx 30\%$ of the injected energy. If the central temperature becomes even smaller, there is no density enhancement

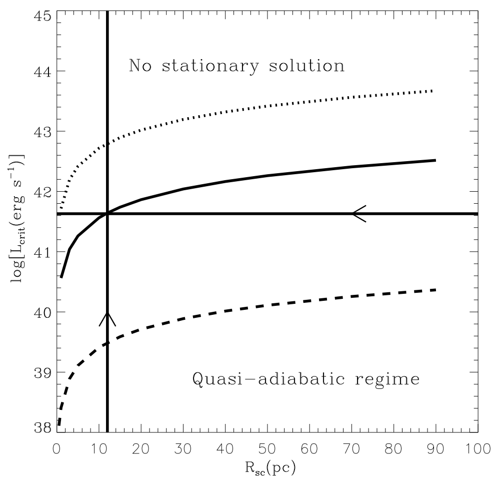

Fig. 2. The impact of radiative cooling. The threshold energy input rate above which the stationary wind solution is fully inhibited, as function of the star cluster radius. The solid line represents the threshold energy for star clusters with $(2q_e/q_m)^{1/2} = V_{\infty A} = 1000$ km s^{-1}. The dotted and the dashed lines mark the threshold energies for star clusters with $(2q_e/q_m)^{1/2} = 1500$ km s^{-1} and 500 km s^{-1}, respectively.

able to compensate 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_{sonic}) cannot be arbitrarily large and has a maximum value for any given set of star cluster parameters.

This conclusion is stressed in Figure 2, which displays the critical energy deposition rate for different values of $q_e/q_m = V^2_{\infty A}/2$. Moving from right to left along the horizontal line is equivalent to considering progressively more compact clusters, all with the same energy and mass deposition rates ($\dot{E}_{sc} \approx 4.4 \times 10^{41}$ 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 (~ 12 pc for the example shown in Figure 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 Figure 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 $L_{crit} \approx 4.4 \times 10^{41}$ erg s^{-1}) and the stationary wind solution vanishes.

4. THE RADIAL WIND STRUCTURE

Star cluster 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 3 presents the free wind temperature distribution for three SSCs, all with the same $R_{sc} = 10$ pc radius and the same ratio $(2q_e/q_m)^{1/2} = V_{\infty A} = 1000$ 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 3, that with 3×10^{41} erg s^{-1} (dashed line), the outer boundary of the X-ray zone ($T_{Xcut} \sim 5 \times 10^5$ K) is about a factor of 1.5 smaller than in the adiabatic case. Furthermore, the dimension at which the gas attains a temperature $\sim 10^4$ K lies about 10 times closer to the star cluster center than in the adiabatic case. Consequently, the maximum density of the emission line envelope is $\sim 10^2$ times larger and the emission measure is $\sim 10^3$ 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 of low intensity at the base of the narrow line caused by the central HII region.

5. WINDS DRIVEN BY MULTIPLE SUPER-STAR CLUSTERS

So far, all calculations in the literature have assumed that the energy deposition arises from a single central star cluster with typical radius of several tens of pc. However, recent optical, IR, radio and X-ray observations revealed an intricate starburst internal structure with a number of space separated compact young stellar clusters. For example, there are more than 100 of them at the center of the prototype starburst galaxy M82, (de Grijs et al. 2001; Muñoz-Tuñón et al. 2004). Many of them are expected to have star cluster winds with properties discussed in the previous sections. Numerical modeling of the interaction of several strong nearby star cluster winds

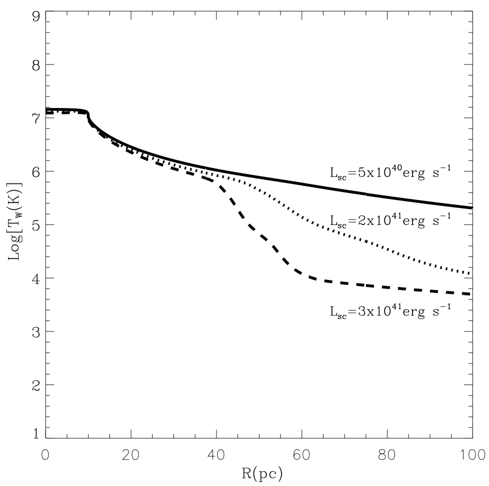

Fig. 3. The impact of cooling in the extended X-ray zone of stationary winds. Temperature profiles for progressively larger energy deposition rates. Solid, dotted and dashed lines represent winds with 0.5, 2 and 3 $\times 10^{41}$ erg s^{-1}, respectively. R_{sc} = 10 pc in all three cases here considered.

opens a new approach for understanding the internal structure and observational manifestations from the starburst driven galactic superwinds (Tenorio-Tagle et al. 2003). The interaction of neighboring cold supersonic winds causes the immediate formation of the oblique reverse shocks that collimates the outflow and form a network of narrow, dense and cold filaments embedded into a hot surrounding medium.

Figures 4 present the development of the self-organized filamentary structure from the three equally powerful superstar clusters sitting at the midplane of the galaxy at 0, 60 and 90 pc from the symmetry axis. All of them with an R_{sc} = 5 pc.

6. CONCLUSIONS

A new self-consistent stationary solution for spherically symmetric radiative winds driven by compact star clusters is proposed. Our model predicts that the radial wind structure may be radically different from what is expected from the adiabatic solution. This implies a much less extended region of X-ray emission, much denser photo-ionized gaseous envelope and a low intensity line emission coming from the compact line cooling zone and photo-ionized envelope.

For super-star clusters with super-critical energy input rates radiative cooling leads to a catastrophic cooling regime where the stationary wind solution is inhibited.

The interaction of multiple winds collimates galactic wind outflows and forms a network of dense and cold filaments embedded into a hot X-ray environment.

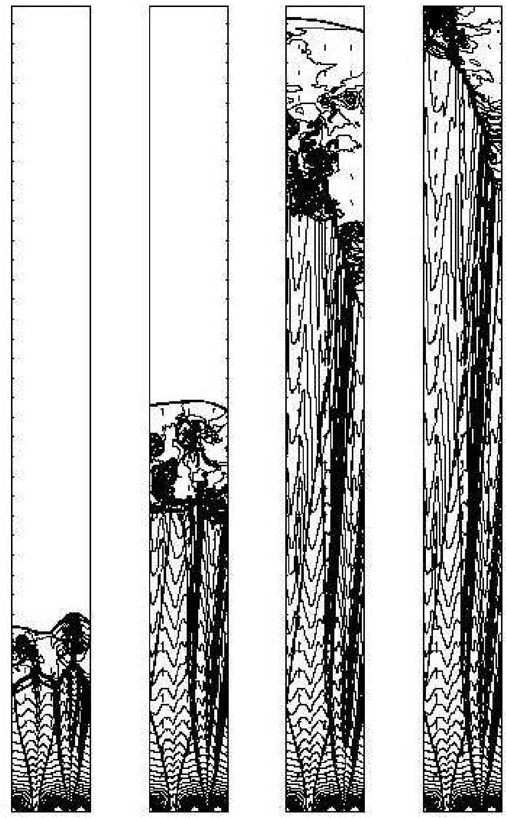

Fig. 4. The multiple winds density distribution. The evolutionary time in the panels is 1.62 $\times$ 10^5 yr, 4.17 $\times$ 10^5 yr, 9.4 $\times$ 10^5 yr and 1.25 $\times$ 10^6 yr, respectively.

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