Hydrodynamic simulations of super star cluster winds

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Abstract

This work shows numerical models of winds driven by super star clusters (SSC) including radiative cooling. The importance of cooling on the wind dynamics depends on the properties of the central cluster: the energy and mass deposition rates $\dot{E}$ and $\dot{M}$, and the cluster radius R_{sc}. Low mass clusters behave in an adiabatic manner, and their winds are well described by the solution of Chevalier & Clegg (1985). However, for larger $\dot{E}$ and $\dot{M}$ and/or smaller R_{sc}, cooling becomes important, and the wind enters the radiative regime in which the wind temperature quickly drops to 10^4 K at a small distance away from the cluster (Silich et al., 2004). There is no stationary wind solution for very energetic and compact clusters.

We use the HD code ZEUS for which we developed a new cooling procedure which is able to deal with extremely fast cooling. We tested our numerical model against the semi-analytical solution of winds in both the adiabatic and the radiative regimes, and continue exploring properties of the winds in more complicated cases with an energy input above the critical value for which the outflow starts to be non-stationary. Our 2D simulations suggest that within the non-stationary regime dense cold clouds may form and be ejected away from the cluster.

Numerical code

The numerical model is based on the finite difference HD code ZEUS. We use the following new cooling routine:

- a tabulated cooling law as a function of temperature and metalicity after Tenorio-Tagle & Różyczka
- the equation for energy is solved implicitly using the Brent algorithm
- the cooling rate is included into time-step computation

$$dt_{\rm cool} = {\rm CCN} \times \frac{e}{\rho\Lambda(T,z)}\,,$$

where ρ and e are the local mass and energy densities, $\Lambda(T,z)$ is the cooling function, and CCN is the "cooling Courant number" – a dimensionless quantity which denotes the relative amount of internal energy that can be radiated away during $dt_{\rm cool}$.

- local sub-steps for the computation of the energy equation are used to increase the code performance; the global time-step is

$$dt = \begin{cases} dt = dt_{\rm HD} & \text{for } dt_{\rm cool} \geq dt_{\rm HD} \\ dt = dt_{\rm cool} & \text{for } dt_{\rm HD} > dt_{\rm cool} \geq \delta \times dt_{\rm HD} \\ dt = \delta \times dt_{\rm HD} & \text{for } \delta \times dt_{\rm HD} > dt_{\rm cool}; \rightarrow \text{local substeps } dt_{\rm sub} = dt_{\rm cool} \end{cases}$$

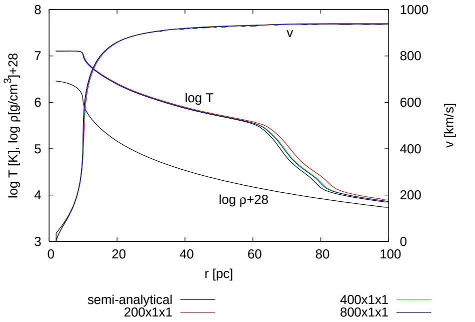
where $dt_{\rm HD}$ is the hydrodynamic time-step and δ (typically ~ 0.1) is a dimensionless parameter.

This procedure does not let the global time-step decrease below $\delta \times dt_{\rm HD}$. However, the accuracy in solving the equation of energy is ensured by the sub-steps of size $dt_{\rm cool}$ which are only applied to fast cooling regions.

Code calibration

We tested the numerical code using the semi-analytical model by Silich et al. (2004) founding a very good agreement. The results does not depend on CCN and δ values (as far as they are smaller than 1), and the numerical solution converges very close to the semi-analytical one with the increasing resolution.

The figure below shows radial profiles of density, temperature and velocity of a wind in the radiative regime. The cluster parameters are $\dot{E} = 3\times10^{41}$ erg/s, $v_{\rm inf} = 1000$ km/s and $R_{\rm sc} = 10$ pc. The density and the velocity are practically the same as in the semi-analytical model, the temperature differs only slightly in the region of fast cooling between 60 and 80 pc.

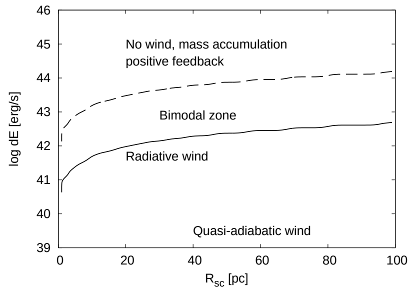


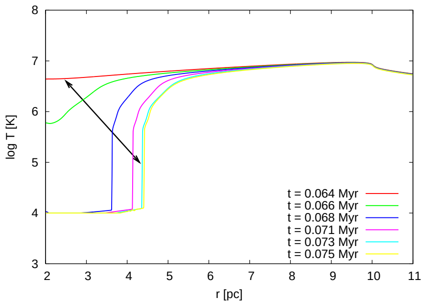
The Hydrodynamics within SSCs

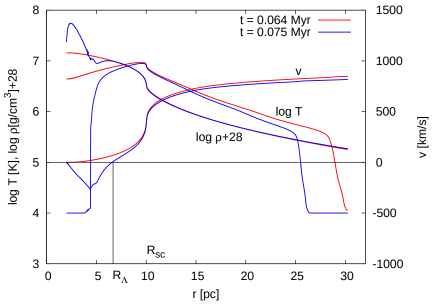
If the cooling rate within the cluster volume exceeds approximately 30% of the energy deposition rate $\dot{E}$, the stationary wind is inhibited (Silich et al, 2004). The solid line in the figure on the right (the threshold line) separates the regions in the parameter space ($\dot{E}, R_{sc}$) able and not able to cause a stationary wind.

Our 1D calculations have led us to infer a new region in the ($\dot{E}, R_{sc}$) plane for which a non-stationary wind may develop. As an example here we show the case of $\dot{E} = 10^{42}$ erg/s, $v_{\rm inf} = 1000$ km/s and $R_{sc} = 10$ pc. The densest central region is clearly the one that cools first but a cooling front rapidly propagates outwards as shown in the figure below. This leads to a sudden drop in pressure that drives the cool matter to flow inwards pass the inner boundary of the calculation. The drop of density decreases the cooling rate and since the energy is replenished continuously, the high temperature ($\sim 10^7$ K) is soon reestablished. Then, the density slowly increases because of mass replenishment, until the gas becomes thermally unstable again and the whole process repeats itself.

These oscillations occurs below the radius R_Λ, above this the velocity of the wind is always positive. Since R_Λ depends on $\dot{E}$, we expect that no wind is possible if $R_\Lambda > R_{sc}$ as suggested by the figures on the right.

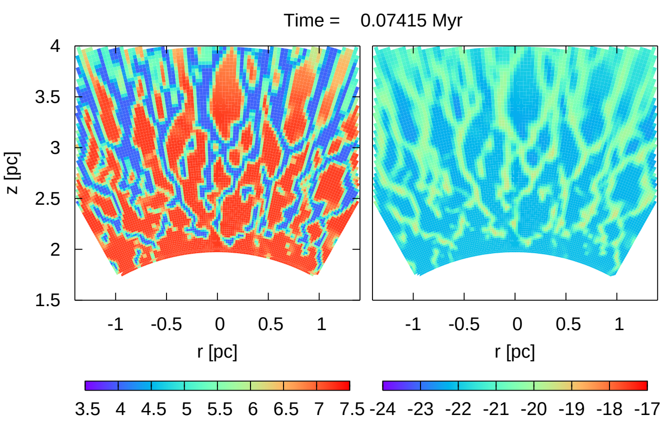


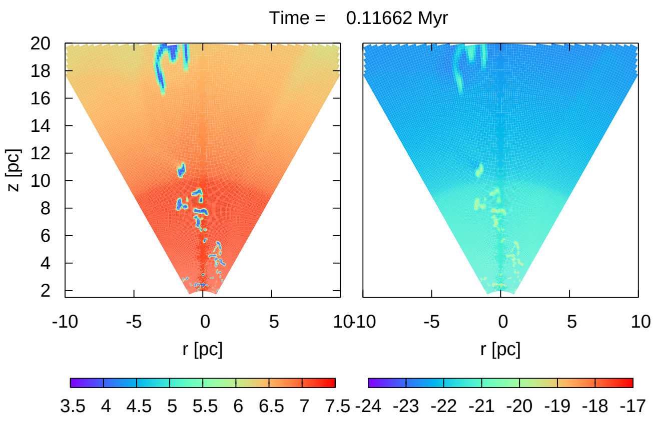




2D simulations

2D simulations with an added random perturbations, with the amplitude 10%, to $\dot{E}$ and $\dot{M}$ break the spherical symmetry. The slightly denser regions cool down rapidly in a practically isochoric way. After a while, the drop in pressure enables the surrounding hot medium to expand and decrease its density and its cooling rate. In this way, a two component medium with dense cold filaments surrounded by a hot rarefied gas is established.





After some time, the velocity field in the cluster region becomes chaotic and the filaments turn into unregular clumps. Some of them fall down and pass the inner boundary. However, energy and mass replenishment into the rarefied gas is able to maintain the the outflow, and several clumps are accelerated and ejected out from the cluster.

Conclusions

SSC above the threshold line present a bimodal intrinsic behaviour. Their densest inner regions are able to cool immediately while in the outer lower densities ones manage to compensate radiative cooling with the energy input rate and thus remain hot and drive a stationary wind. Such clusters present in 1D an inward velocity field over all the matter continuously overtaken by the re-current cooling fronts. Further out the velocity goes from 0 km/s to the local sound speed value right at the cluster edge and thus the wind is stationary. In 2D cooling leads to a filamentary structure which later breaks into a collection of clouds, some of which may be ejected from a cluster within a cooling time.

References:

Chevalier, R. A., Clegg, A. W., 1985, Nature, 317, 44
Silich, S., Tenorio-Tagle, G., Muñoz-Tuñón, C., 2003, ApJ, 590, 791
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