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The Formation of Catastrophically Cooling Outflows in Star-forming Regions via Non-equilibrium Radiative Cooling

Ashkbiz Danehkar, M. S. Oey, and William J. Gray

Department of Astronomy, University of Michigan, 1085 S. University Ave, Ann Arbor, MI 48109, USA

ABSTRACT

Multiwavelength surveys of star-forming regions suggest the presence of catastrophically cooling outflows. Mechanical feedback from super star clusters in starburst regions can produce cooling galactic-scale outflows, but outflows predicted by the adiabatic models cannot lead to strong cooling seen in several star-forming galaxies such as M82 and NGC 2366. We simulate starburst-driven outflows using the MAIHEM non-equilibrium cooling package built on the hydrodynamics code FLASH to determine the existence domains of catastrophic cooling, in the parameter space of the metallicity, mass-loading, kinetic heating efficiency, and ambient density. Although the metallicity has a major role in cooling, radiative cooling is significantly enhanced by increasing mass-loading and decreasing kinetic heating efficiency. Our results demonstrate the significance of radiative cooling for star-forming regions, where coolants could be responsible for the build-up of cold molecular hydrogen (H_2) clumps leading to the star formation.

INTRODUCTION

Starburst-driven galactic-scale outflows usually appear in starburst regions, which are created by stellar winds from OB associations in super star clusters (e.g., Heckman et al. 1990; Oey & Massey 1995). The physical properties of starburst-driven outflows have been modeled using the adiabatic assumptions (Weaver et al. 1977; Chevalier & Clegg 1985). According to Weaver et al. (1977), this type of outflows has four regions: (1) freely expanding wind, (2) hot bubble, (3) shell, and (4) ambient medium (see Fig. 1).

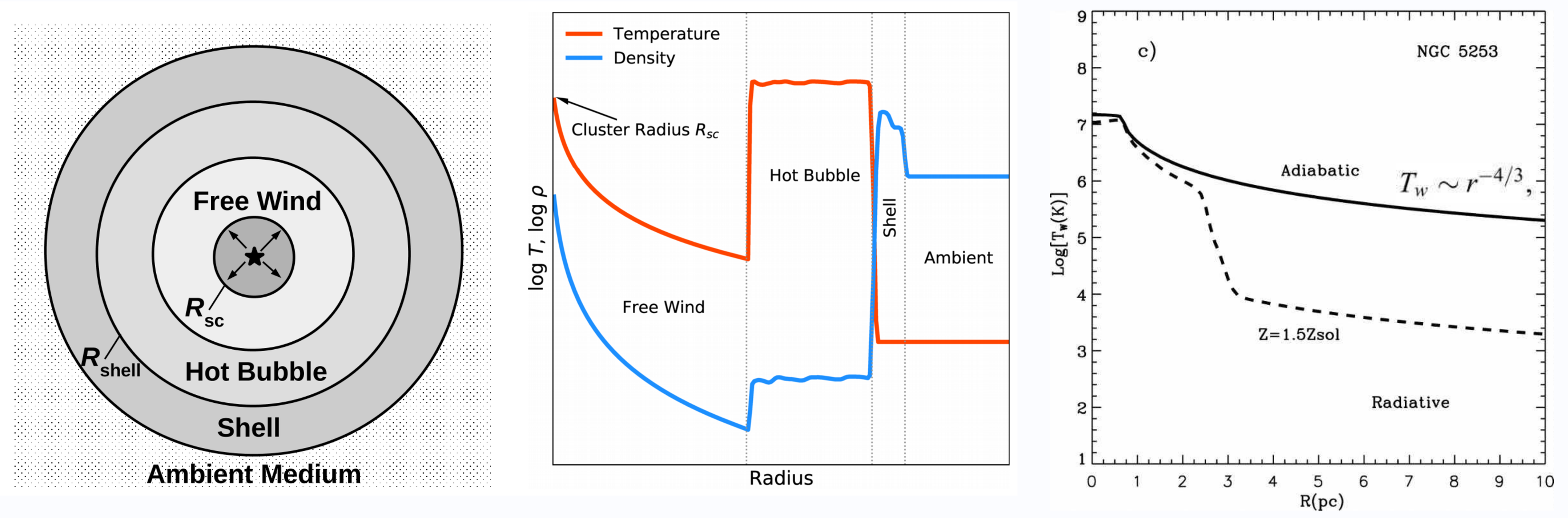


FIG 1. From Left to Right, a schematic view an galactic-scale starburst-driven outflow, temperature and density profiles with 4 different regions refined by Weaver el al. (1997), followed by the analytic adiabatic and radiative solutions from Silich et al. (2004).

The adiabatic solutions of the fluid model obtained by Chevalier & Clegg (1985) indicate that the density and temperature profiles in the freely expanding wind region decline with radius r as $\rho_w \sim r^{-2}$, $T_w \sim r^{-4/3}$, see Fig. 1. The semi-analytic radiative solutions studied by Silich et al. (2004) imply that there are departures from the adiabatic solutions (Fig. 1), i.e. *catastrophic cooling*. Observations of some starburst galaxies such as M82 and NGC 2366 support the presence of catastrophic cooling in some regions (Smith et al. 2006; Oey et al. 2017; Turner et al. 2017).

HYDRODYNAMIC SIMULATIONS

We conducted hydrodynamic simulations of starburst-driven outflows generated by feedback from a spherically symmetric super star cluster (SSC) characterized by the cluster radius (R_{sc}), mass deposition rate ($\dot{M}$), wind terminal velocity (V_∞), and stellar ionizing fields described by ionizing luminosity (L_{ion}) and spectral energy distribution (SED) surrounded by ambient medium (density n_{amb} and temperature T_{amb}) using the non-equilibrium cooling package MAIHEM (Gray ey al. 2019) built on FLASH (Fryxell et al. 2000).

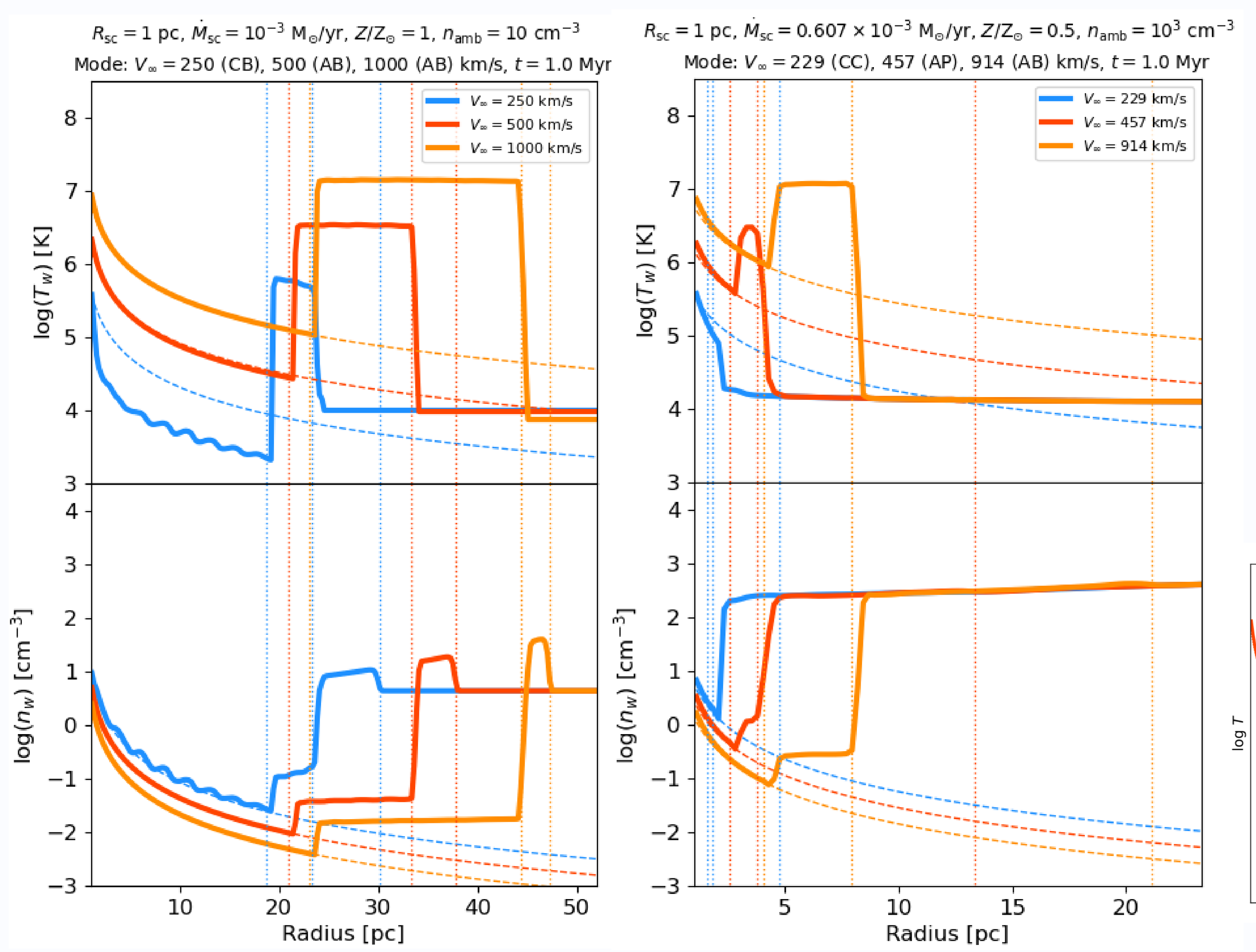
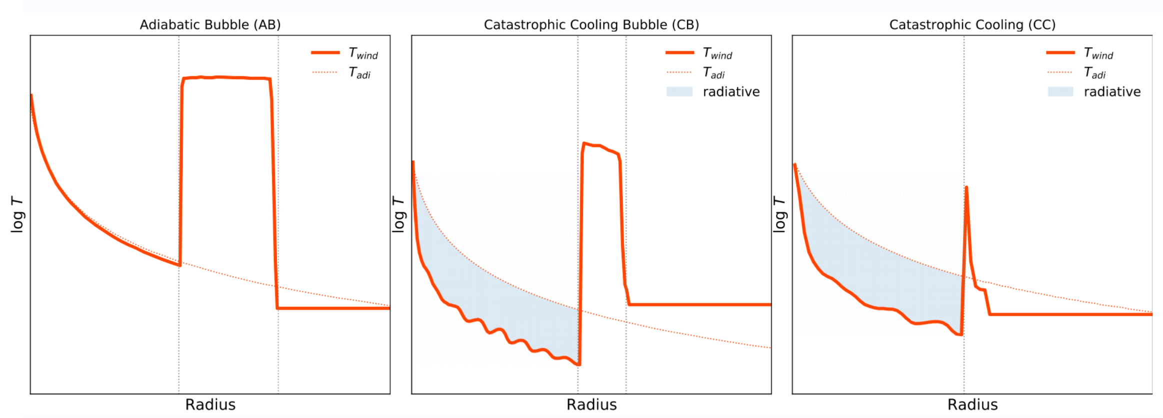


FIG 2. Two examples of density and temperature profiles produced by our hydrodynamic simulations from Danehkar et al. (2021). The wind parameters are given in the top captions. The adiabatic temperature and density profile shown by dashed lines. The different wind regions separated by dotted lines, see superwinds.astro.lsa.umich.edu

FIG 3. Different wind modes classified according to temperature profiles, namely adiabatic bubble (AB), catastrophic cooling bubble (CB), and catastrophic cooling (CC), see Danehkar et al. (2021). The adiabatic solutions shown by red dotted lines. The boundaries of the bubble shown by gray dotted lines. Radiative cooling make departures from the predicted adiabatic profiles.



CATASTROPHIC COOLING CONDITIONS

According to departures from adiabatic profiles (see Fig. 3), we classify our hydrodynamic results as *adiabatic bubble* (AB) mode with temperature profiles predicted by Chevalier & Clegg (1985) and bubbles (Weaver et al. 1977), *catastrophic cooling* (CC) mode without bubbles with temperature profile similar to Silich et al. (2004), and *catastrophic cooling bubble* (CB) mode, see Fig. 4.

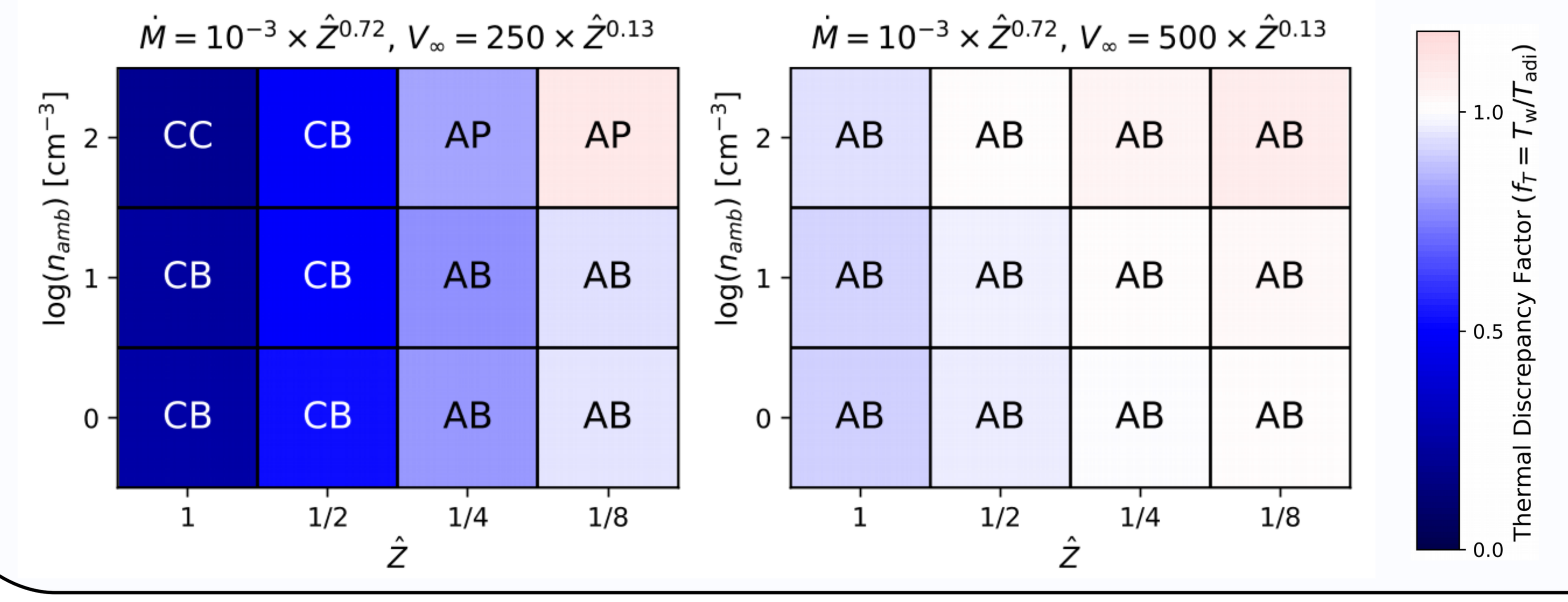


FIG 4. The radiative temperature profile relative to the adiabatic temperature profile in the freely expanding wind regions. Outflows are classified under the adiabatic bubble (AB), the catastrophic cooling (CC), thhe catastrophic cooling bubble (CB), see Fig. 3, as fully described by Danehkar et a. (2021).

PHOTOIONIZATION MODELS

Photoionization models are produced by CLOUDY (Ferland et al. 2017) using our hydrodynamic results, together with the SED of the ionizing source made by Starburst99, for two different cases: (1) photoionization without hydrodynamic effects (*PI*) built by the density profile from our hydrodynamic results; and (2) photoionization combined with hydrodynamic collisional ionization (*CPI*) constructed using the density and temperature profiles generated by our hydrodynamic simulations, see Fig. 5.

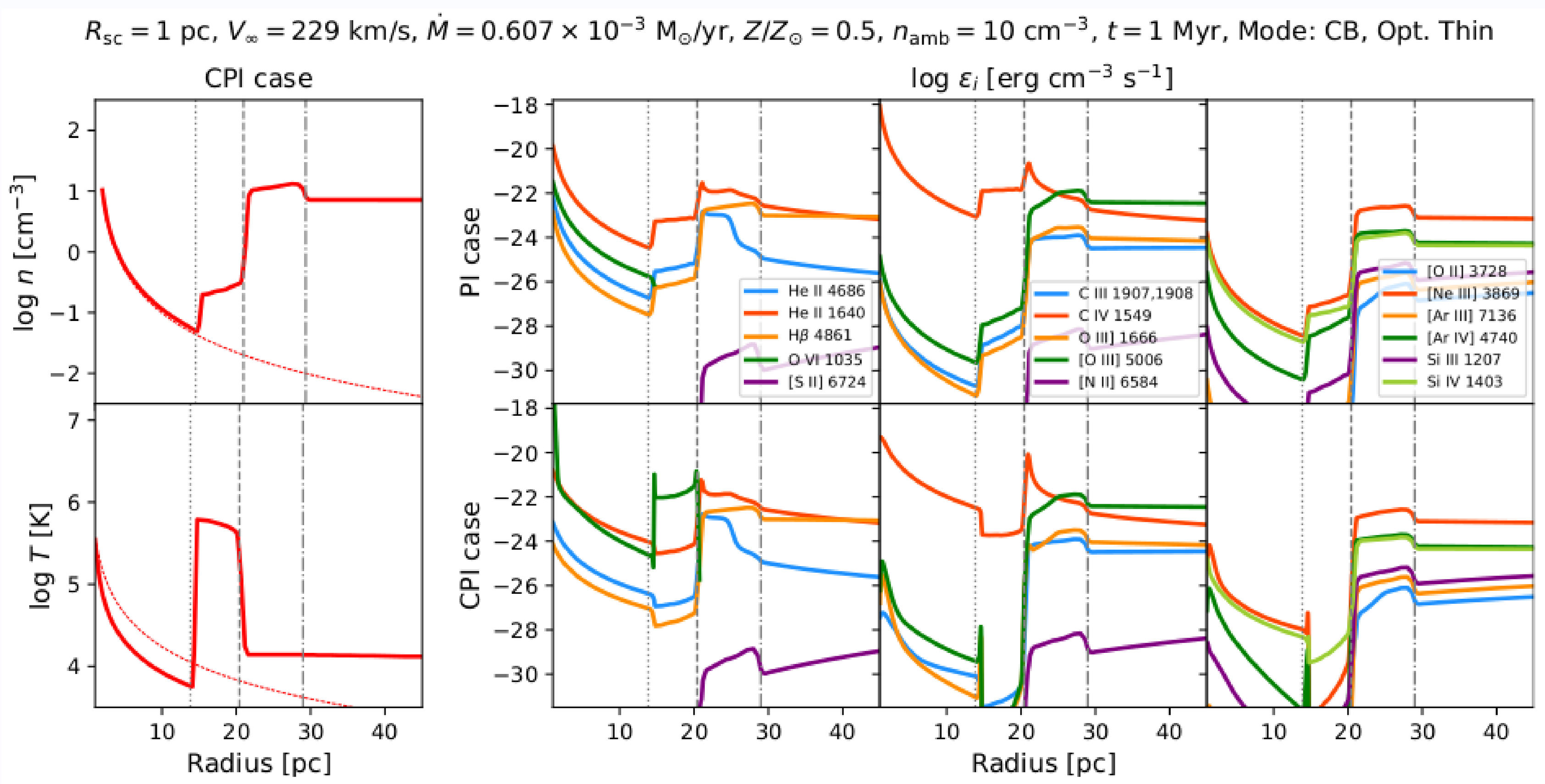


FIG 5. The density and temperature profiles in the CPI case (left panels) along with the adiabatic profiles (red dashed lines), and the emissivities of lines (right panels) in the PI and CPI cases, for values of the cluster radius (R_{sc}), wind terminal speed (V_∞), mass-loss rate ($\dot{M}$), metallicity (Z), ambient density (n_{amb}), and age t given at the top. The start (dotted) and end of the bubble (dashed), and the end of the shell (dashed–dotted) shown. The wind mode (CB, here) and optical depth also specified, from Danehkar at al. (2021), see superwinds.astro.lsa.umich.edu

CONCLUSION

Our hydrodynamic simulations imply that while the *metallicity plays a major role in catastrophic cooling, higher mass-loading and lower kinetic heating efficiency lead to stronger cooling* in star-forming galaxies where the metallicity is relatively low. Moreover, the *presence of superbubbles does not imply an adiabatic outflow, and vice versa*. Our CLOUDY photoionizaion models indicate that while the radiation-bounded line flux ratios are in agreement with observations, diagnostics of catastrophically cooling outflows require other constraints, and implications of non-equilibrium ionization and radiative transfer should be investigated in future works.

REFERENCES

Chevalier R. A. and Clegg A. W. 1985 Natur 317 44
Danehkar A., Oey M. S. and Gray W. J. 2021 ApJ, arXiv:2106.10854
Ferland G. J., Chatzikos M., Guzmán F. et al 2017 RMxAA 53 385
Fryxell B., Olson K., Ricker P. et al 2000 ApJS 131 273
Gray W. J., Oey M. S., Silich S. and Scannapieco E. 2019 ApJ 887 161
Heckman T. M., Armus L. and Miley G. K. 1990 ApJS 74 833
Leitherer C., Ekström S., Meynet G. et al 2014 ApJS 212 14
Oey M. S., Herrera C. N., Silich S. et al 2017 ApJL 849 L1
Oey M. S. and Massey P. 1995 ApJ 452 210
Silich S., Tenorio-Tagle G. and Rodríguez-González A. 2004 ApJ 610 226
Smith L. J., Westmoquette M. S., Gallagher J. S. et al 2006 MNRAS 370 513
Turner J. L., Consiglio S. M., Beck S. C. et al 2017 ApJ 846 73
Weaver R., McCray R., Castor J., Shapiro P. and Moore R. 1977 ApJ 218 377

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E-mail: danehkar@umich.edu