HEATING THE INTRA-CLUSTER MEDIUM PERPENDICULAR TO THE JETS AXIS

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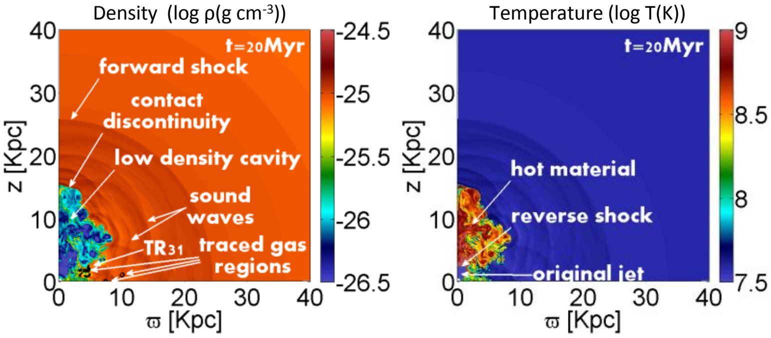
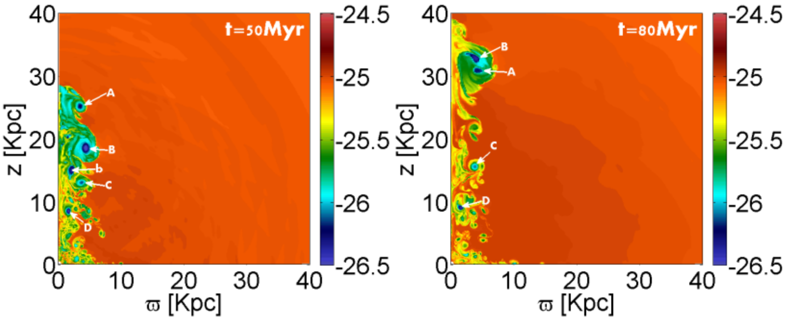
ABSTRACT: By simulating jet-inflated bubbles in cooling flows with the PLUTO hydrodynamic code (Mignone, A., Bodo, G., Massaglia, S., et al. 2007, ApJS, 170, 228) we show that mixing of high entropy shocked jet's material with the intra-cluster medium (ICM) is the major heating process perpendicular to the jets' axis. Heating by the forward shock is not significant. The mixing is very efficient in heating the ICM in all directions, to distances of ~10kpc and more. Although the jets are active for a time period of only 20Myr, the mixing and heating near the equatorial plane, as well as along the symmetry axis, continues to counter radiative cooling for times of t>10^8yr after the jets have ceased to exist.

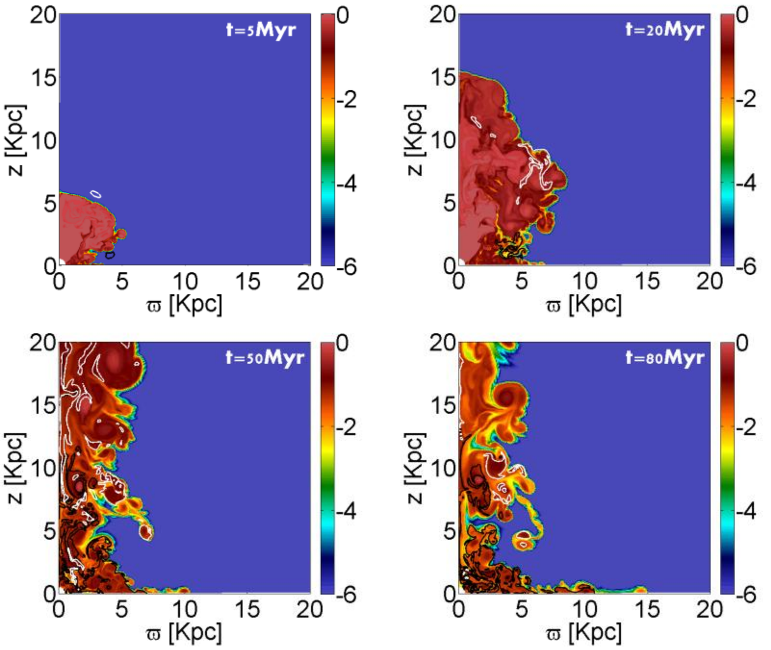
FURTHER IMPLICATIONS: (1) The vigorous mixing is expected to entangle magnetic field lines, hence to suppress any global heat conduction in the ICM near the center. (2) The vigorous mixing forms multi-phase ICM in the inner cluster regions, where the coolest parcels of gas cool first, flow inward, and feed the AGN to set the next jet-activity episode. This further supports the cold feedback mechanism. (3) In cases where the medium outside the region of r~10kpc is not as dense as in groups and clusters of galaxies, like during the process of galaxy formation, the forward shock and the high pressure of the shocked jets' material can expel gas from the system.



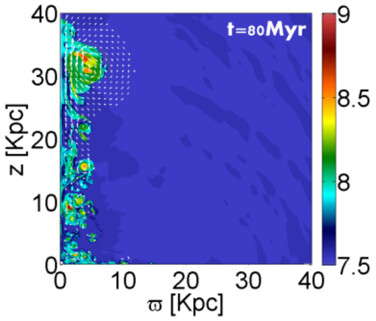
The flow structure at t=20Myr in the (ϖ,z) plane, where z is along the symmetry (jet) axis and ϖ is in the equatorial plane. The simulation is 3D with axisymmetry imposed, namely, a 2.5D simulation. Due to our 2.5D grid, each traced region is a thin torus.



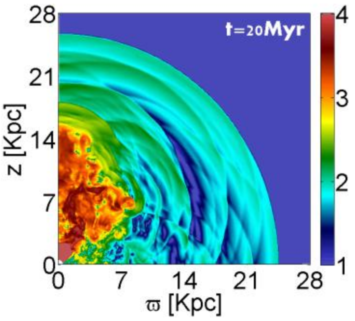
The density maps in the (ϖ,z) plane at two times. Density scale is in units of log ρ(g cm^{-3}). We follow the position of five vortices and mark them on the panels. Vortex b merges with vortices A and B, and is therefore not clearly seen at t=80Myr.



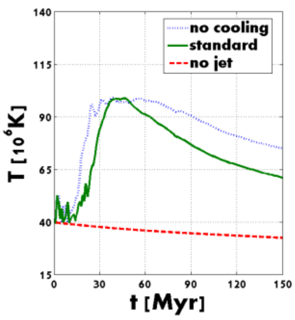
The concentration of jet material ξ (fraction of jet's material at each point) is shown by the color coded map in logarithmic scale at four times. It is clearly seen that the jet's material mixes with the ICM. We also follow the material of two tracers, TR31 and TR24. Here TR31 is the gas that started inside the circular region centered on (ϖ,z)=(3,1)kpc and having a radius of 0.25kpc, with a similar definition for TR24. The black (white) contours show where the concentration of TR31 (TR24) is one percent. Most of the TR24 gas is carried with the jet's gas along the symmetry axis. The TR31 gas suffers vigorous mixing near the center, and is heated up by this mixing.



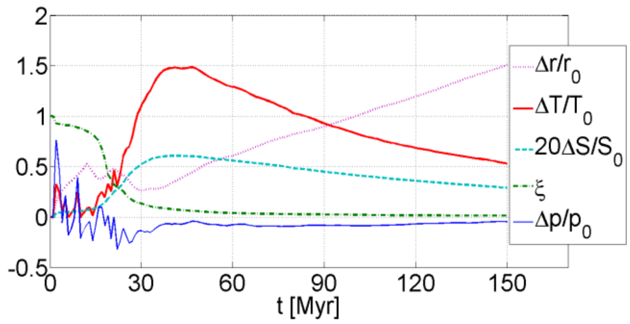
Velocity and temperature map at t=80Myr. The velocity vectors are divided into four groups by their length, from longest to shortest in km s^{-1}: 5000<v, 1000<v≤5000, 200<v ≤1000, and 50<v ≤200.



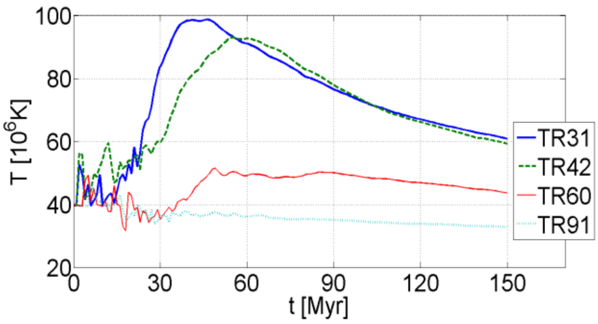
The velocity map. Scale is in units of log v(km s^{-1}).



Average temperature of TR31 for three cases: (i) standard run; (ii) no radiative cooling; (iii) no jet.



Variation of the relative change in average pressure, temperature, location, entropy (calculated from average ρ and T), and the mixing degree ξ, of the traced region TR31. Both temperature and entropy clearly show that the major heating process is mixing, indicated by decreasing value of ξ, and not the forward shock that hits the boundary of the tracer at t=1Myr. The decrease in temperature and entropy at late times is due to mixing with cooler ICM regions. The cooling of the tracer comes with heating more ICM.



Average temperature of four traced regions as function of time. Each region is marked by its starting location in the (ϖ,z) plane.