Inflating a Chain of X-ray Deficient Bubbles by a Single Jet Activity Episode

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We show that a continuous jet with time-independent properties can inflate a chain of close and overlapping X-ray deficient bubbles. Using the numerical code PLUTO [1] we run 2.5D hydrodynamic simulations and study the interaction of the jets with the intra-cluster medium (ICM). A key process is vortex fragmentation due to several mechanisms, including vortex-shedding and KH-instabilities. Our results can account for the structure of two opposite chains of close bubbles as observed in the galaxy cluster Hydra A [3] and galaxy group NGC 5813 [2]. Our results imply that the presence of multiple pairs does not necessarily imply several jet-launching episodes. This finding may have implications to the feedback mechanism operating by jets.

Numerical Setup

We use a spherical coordinate system, but impose cylindrical symmetry, hence calculating the flow with a 2D polar grid (r, θ). $1 \le r \le 400$ kpc and $0 \le \theta \le \frac{\pi}{2}$.

The **boundary conditions** are reflective on both 'angular' boundaries: the symmetry axis $\theta = 0$ and the equatorial plane $\theta = \pi/2$, and an outflow condition on the outer radial boundary. The **jet is injected** by using the boundary conditions at $r = 1$ kpc. The jet is injected within an angle $0 \le \theta \le \alpha$ – where α is the half-opening angle. At other angles on the inner radius we impose reflective boundary conditions. Our flow is **non-relativistic**. **Gravity is included**, but as the simulations last for a time shorter than the radiative cooling time we neglect radiative cooling.

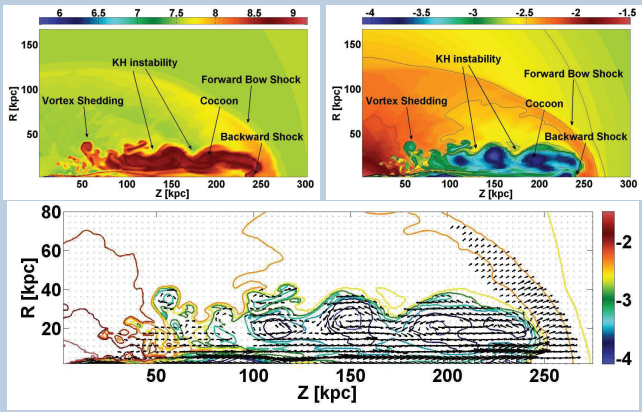
Model Parameters

The initial **density profile** is based on that of Hydra A. In the inner 10 kpc we approximate the profile by a constant density of $n_e = 0.06$ cm^{-3}, where n_e is the electron density, at $r > 10$ kpc the density drops as $n_e(r) \propto r^{-1}$. The initial **temperature** of the gas is constant across the entire domain $T_0 = 3.5$ keV. The **gravity** is calculated from the initial pressure and density profiles by assuming hydrostatic equilibrium $g = -\frac{1}{\rho_0(r)} \frac{dP_0(r)}{dr}$. The parameters of the standard run are: Total **two jets power** of $P_{2j} = 4 \times 10^{45}$ erg s^{-1}. **Initial jet velocity** of $v_j = 1.33 \times 10^4$ km s^{-1}. **Mass outflow** from the two opposite jets (here we calculate only one jet) is $\dot{M}_{2j} = 70 M_\odot$ yr^{-1}, and the jet half-opening angle is $\alpha = 30°$.

References

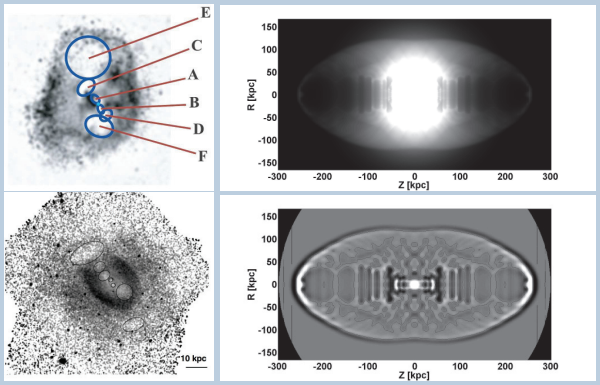
[1] Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O., Zanni, C., Ferrari, A., 2007, ApJS, 170, 228
[2] Randall, S. W., et al. 2011, ApJ, 726, 86
[3] Wise, M. W., McNamara, B. R., Nulsen, P. E. J., Houck, J. C., & David, L. P. 2007, ApJ, 659, 1153

Morphology



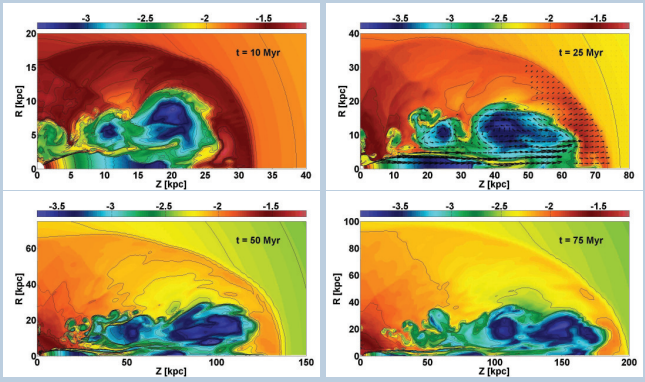
Results of the standard run at $t = 100$ Myr. **Upper Left:** The temperature map of the standard run in logarithmic scale and units of K. **Upper Right:** The electron density in logarithmic scale and units of cm^{-3}. **Bottom:** Contours of the electron density in logarithmic scale and velocity arrows.
The fragmented vortices, that are at the heart of the present study, are marked. Vortex shedding region is also marked.

X-ray Images - Observations and Simulation



To compare with observations we integrated the quantity n_e^2 along the line of sight perpendicular to the symmetry axis. To emphasize the cavities we applied Gaussian unsharp filter to the integrated map. **Upper left:** Hydra A bubbles (taken from [3]). **Bottom left:** NGC 5813 bubbles (taken from [2]). **Upper right:** X-ray map from our standard run. **Bottom right:** X-ray map from our standard run after applying unsharp filter. '1' contours are plotted.

Evolution



Density maps of the standard run at four times. The color scaling is of $\log n_e(\text{cm}^{-3})$, where n_e is the electron density. A primary vortex right behind the jet's head and another vortex trailing it exist during the evolution. At the $t = 10$ Myr picture the flapping of the jet may be seen as a perturbation on the separating layer between the expanding jet and the cocoon.

Conclusions

- We have shown that one jet activity episode can form two opposite chains of close bubbles.
- Chains of close and overlapping X-ray cavities can be created by a combination of various vortex fragmentation mechanisms, mainly KH-instability and vortex-shedding.
- Large separations between bubbles, probably require multiple jet activity episodes.

Acknowledgements

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