X-ray Cavities Created With Cosmic-ray-dominated AGN Jets

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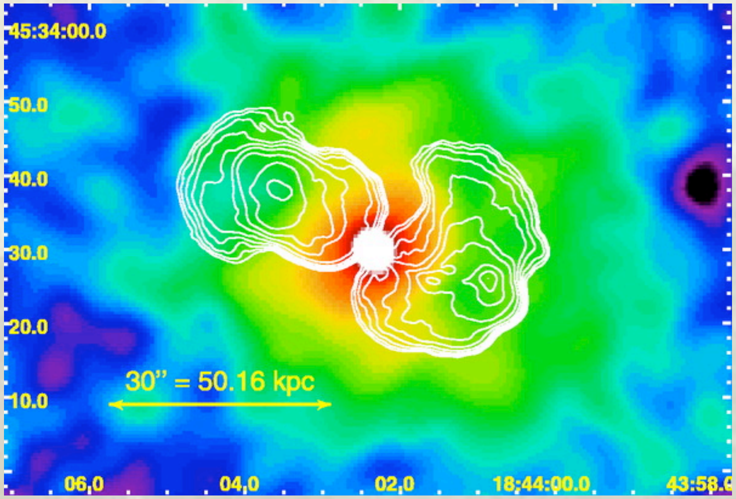
Reference –

Guo & Mathews, 2011, ApJ, 728, 121

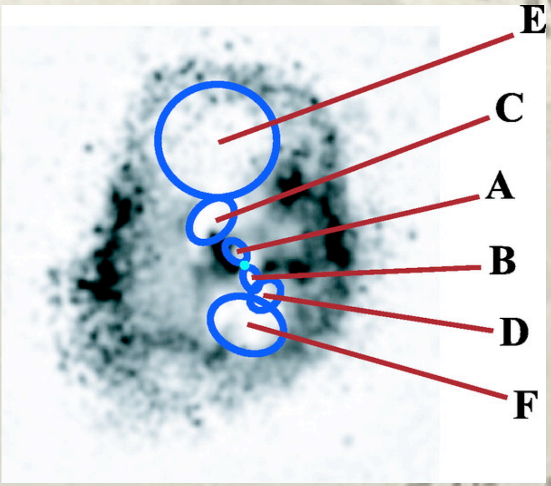
Abstract

AGN feedback plays a key role in the evolution of gas in galaxy groups and clusters. The strongest evidence for AGN feedback comes from mounting observations of quasi-spherical X-ray cavities and radio bubbles near cluster centers. Using numerical simulations with a self-consistent treatment of the cosmic ray-gas interaction, we show that AGN jets producing these cavities are very light (jet-ICM density contrast <~ 0.001), and energetically dominated by cosmic rays. More massive jets dominated by kinetic energy typically penetrate deep into the intracluster medium, forming cavities strongly elongated in the jet direction unlike those observed.

Radio Bubbles and X-ray Cavities in Observation



3C 388, X-ray image with 5GHz radio contours (Kraft et al 2006)



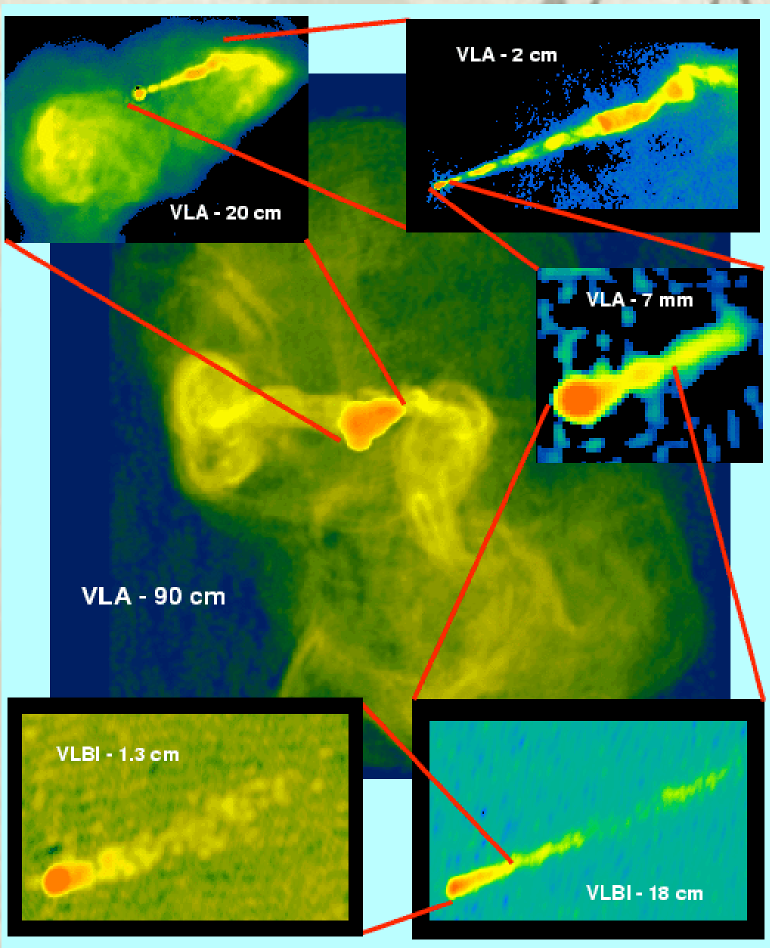
Hydra A, X-ray cavities (Wise et al 2007)

- AGN feedback is increasingly recognized to play an important role in the evolution of elliptical galaxies, galaxy groups and clusters, e.g., solving the cooling flow and over cooling problems.
- The strongest evidence for AGN feedback comes from numerous detections of X-ray-deficient cavities, some of which are associated with radio jets and bubbles.

AGN Feedback in the Virgo Cluster

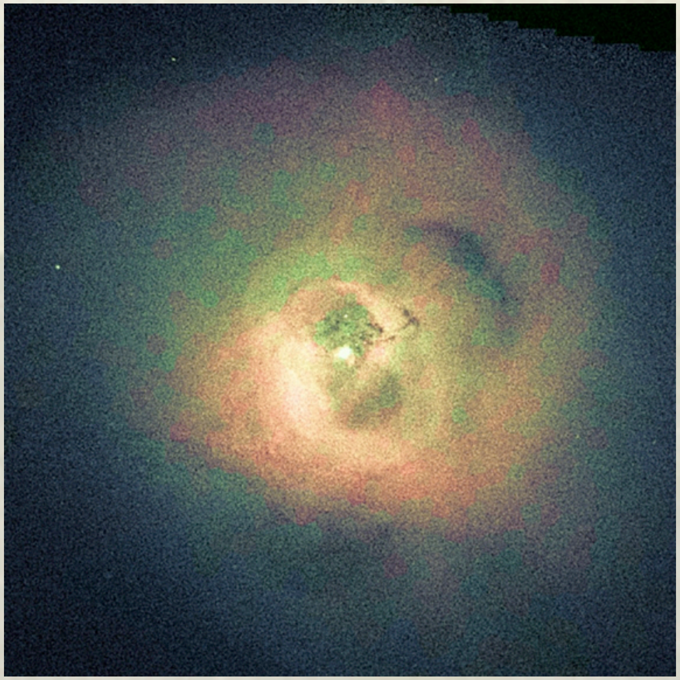
- X-ray cavities and radio bubbles are likely produced by AGN jets ejected from supermassive black holes located at the centers of galaxy groups and clusters.

- AGN jets carry relativistic cosmic rays, which emit radio synchrotron emission in magnetic fields and contribute to the pressure within the jets.



Credit: F. Owen, J. Biretta, and colleagues

Cavity Shape and Location



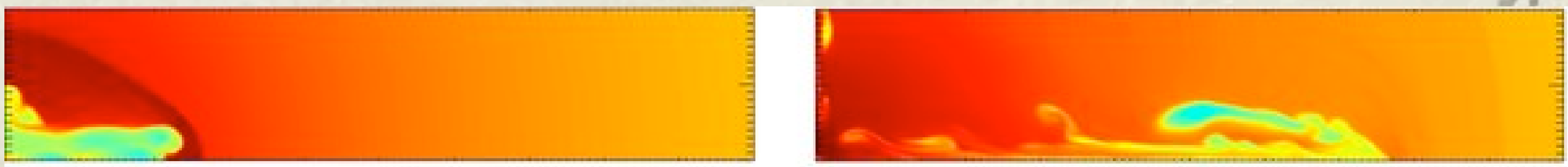
Chandra image of Perseus Cluster (Fabian et al 2006)

- Most observed cavities are located near cluster centers, and are roughly spherical or even elongated in the direction perpendicular to the radial jet axis.
- Cavities seem to rise buoyantly in the ICM.

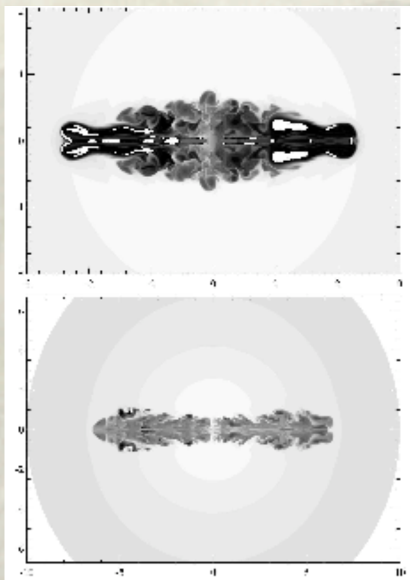
The Physics of AGN Jet Feedback

- Previous studies focus on the impact of AGN feedback on host clusters. Here we are studying the detailed physics of AGN feedback.
- Can we use the observations of AGN feedback to constrain the jet properties?
- How to correctly model AGN feedback in numerical simulations?

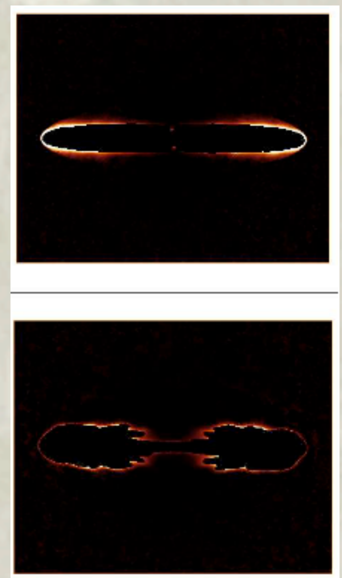
The Cavity Formation Problem



Log (electron number density) Guo & Mathews 2011 Log (electron number density)



Reynolds et al 2002



O’Neill & Jones, 2010

- Jet simulations usually adopt light thermal jets with typical jet-to-ICM density contrasts: \eta ~ 0.01 - 0.1. These jets are dominated by kinetic energy, and penetrate through the ICM quickly, forming radially-elongated cavities at large radii, unlike observed cavities. We call this ‘the cavity formation problem’.

Previous solutions to the cavity formation problem

- Wide jets with half opening angles >~ 50° (Sternberg et al. 2007)
- fast precessing jets with large precessing angles (Sternberg & Soker 2008)
- Large random gas motions in the ICM (Brüggen et al 2007; Morsony et al 2010)

Our Solution: Very Light Cosmic-ray-dominated Jets

- 'Fat' X-ray cavities are naturally formed if AGN jets are much lighter then typically assumed. We assume a typical density contrast of 1/10000 instead of 1/100 (broadly speaking, \eta <~ 0.001 is required). Lower inertia and momentum insure that the jets decelerate quickly in the ICM.

- The jets are energetically dominated by relativistic cosmic rays, which provide pressure, expanding the jets and cavities laterally, and thus forming quasi-spherical cavities.

- The CR-dominated jet contains both thermal and CR components --- two-fluid jet. The internal energy and pressure of the jet are dominated by the CR component, while its density and momentum are dominated by thermal gas, and are very small.

Numerical Methods

- Our Code: 2D, Axisymmetric, finite-differencing, Eulerian code

- Implementing self-consistent CR-gas interaction, following the CR evolution. All the CRs enter into the ICM in the jet.

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0, \tag{1}$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla (P + P_c) - \rho \nabla \Phi, \tag{2}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{v}) = -P \nabla \cdot \mathbf{v}, \tag{3}$$

$$\frac{\partial e_c}{\partial t} + \nabla \cdot (e_c \mathbf{v}) = -P_c \nabla \cdot \mathbf{v} + \nabla \cdot (\kappa \nabla e_c) + \dot{S}_c, \tag{4}$$

RESULTS

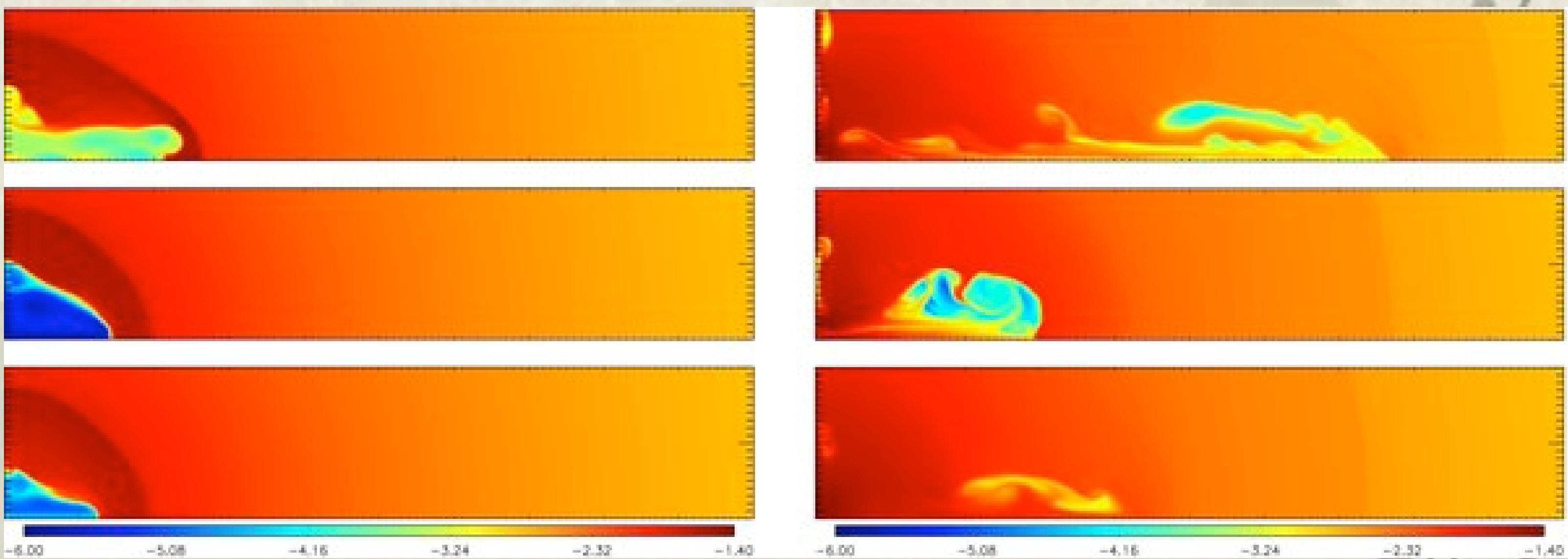


Fig. 1 - Central slices (100 × 20 kpc) of log (n_e/cm^–3) in runs J0 (top panels), J1 (middle panels), and J1-A (bottom panels) at time t = 10 Myr (left panels) and t = 70 Myr (right panels). n_e represents the electron number density. Run J0 is a typical thermal jet with density contrast eta=0.01. Run J1 is a typical CR-dominated jet with \eta=0.0001 and has the same jet power as run J0. Run J1-A is a very light thermal jet with eta=0.0001 (the same as run J1 except no CRs). All the jets are turned off at t=10 Myr. Guo & Mathews 2011.

- As clearly seen in Fig. 1, the thermal jet J0 penetrates through the ICM quickly, forming a radially-elongated cavity, and its radial motion is clearly driven by the initial jet momentum during the whole simulation $0 < t < 100$ Myr. In contrast, the very light CR-dominated jet J1 decelerates quickly, particularly after the jet was turned off at t=10 Myr. The jet forms a fat cavity, which rises buoyantly in the ICM since t ~ 20 Myr.

RESULTS

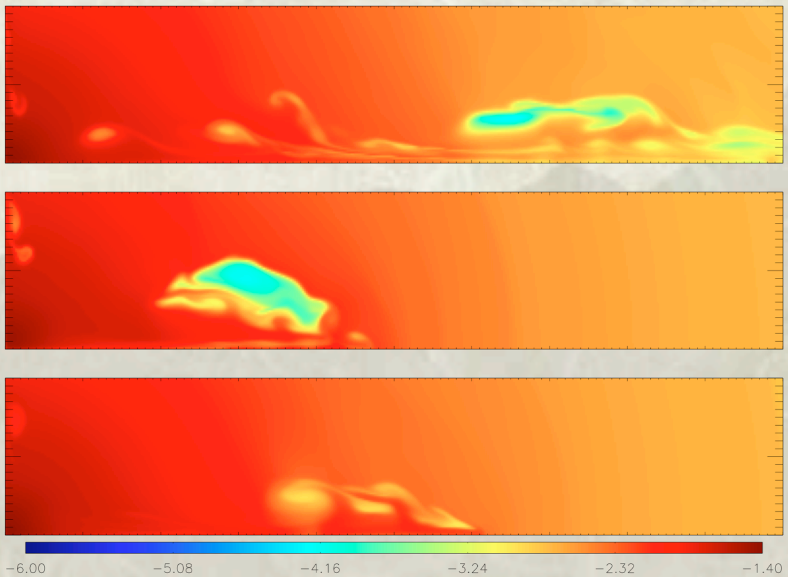


Fig. 2 - Central slices (100 × 20 kpc) of log (n_e/cm^–3) in runs J0 (top panels), J1 (middle panels), and J1-A (bottom panels) at time t = 100 Myr. Guo & Mathews 2011.

- The very light thermal jet J1-A does not contain CRs, and is significantly under-pressured. The formed low-density cavity is much smaller and elongated in the radial direction. CR pressure induces lateral expansion of the jet and cavity, which is the key to make cavities fat or spherical. If the jet has the same pressure as in run J1, the gas temperature in the jet must be relativistically hot.

Projected X-ray Image - X-ray Cavities

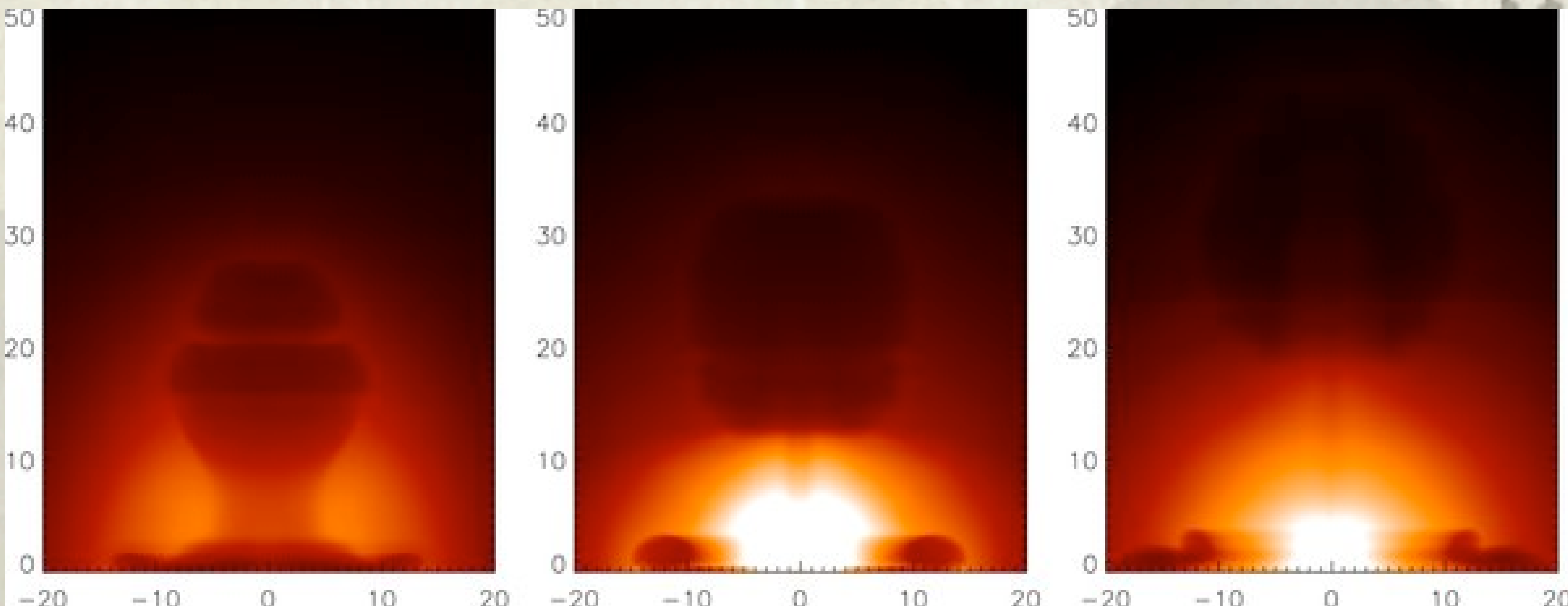


Fig. 3 - Central regions (50 × 40 kpc) of synthetic X-ray surface brightness maps (line of sight integrated projections of the cooling rate perpendicular to the jet axis) for run J1 at t = 60 (left panel), 80 (middle panel), and 100 Myr (right panel). The cavity is clearly seen as it rises in the ICM. Guo & Mathews 2011.

Jet Propagation

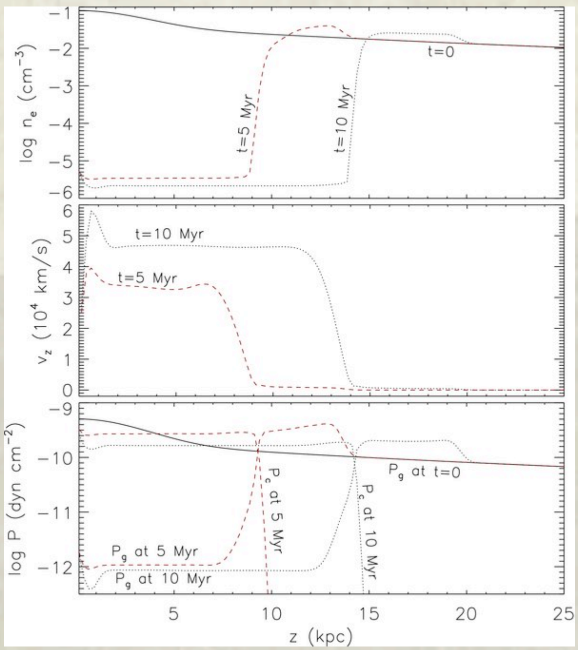


Fig. 4 Variations of electron number density (top), the z-component gas velocity (middle), and pressures (bottom) along the jet axis for run J1 at t = 5 Myr (dashed) and t = 10 Myr (dotted). The initial gas density and pressure profiles along the z-axis at t = 0 are plotted as solid lines in the top and bottom panels, respectively. Note that the jet is initialized in ghost zones, which are not plotted. Guo & Mathews 2011.

- Figure 4 shows that the jet produces a weak shock enclosing the low-density cavity. Within the jet and cavity, CR pressure dominates over the thermal pressure in our main run J1. The cavity and ambient shocked gas are separated by a contact discontinuity, across which the total pressure is continuous.

The Lateral Expansion of Jet Tips Driven by CR Pressure

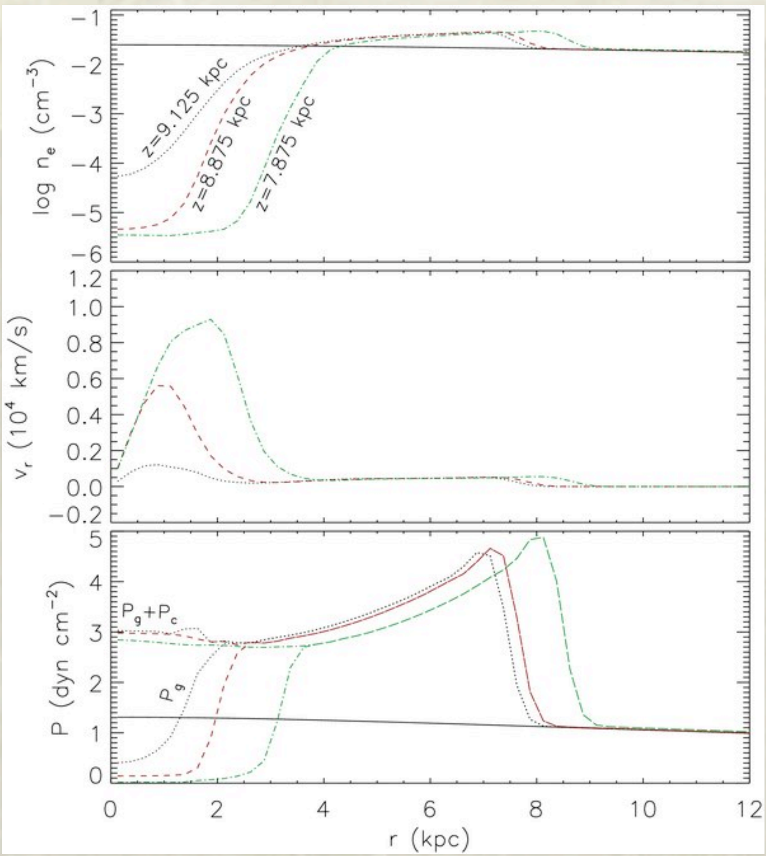


Fig. 5 Variations of electron number density (top), the r-component gas velocity (middle), and pressures along the r-direction (perpendicular to the jet axis) for run J1 at z = 9.125 (dotted lines), 8.875 (dashed lines), and 7.875 kpc (dot-dashed lines) at t = 5 Myr. The initial gas density and pressure profiles along the r-axis at z = 9.125 kpc are plotted as solid lines in the top and bottom panels, respectively. Near the jet axis, the gas pressure drops significantly in the low-density cavity where CR pressure dominates.Guo & Mathews 2011.

- At t=5 Myr, the jet head is located near z = 7 - 9 kpc. As shown in Figure 5, the jet head expands laterally (positive velocity in the r direction) , driven by CR pressure within the jet. The lateral expansion allows the jet to encounter and displace more ICM gas, strengthening its deceleration.

Summary - The Physics of AGN Jet Feedback

- The shape and location of X-ray cavities can be used to constrain the properties of AGN jets.

- The detection of numerous ‘fat’ X-ray cavities near cluster centers indicates that the responsible AGN jets are very light and energetically dominated by cosmic rays.

- AGN feedback events may also happen regularly in the Milky Way. Check out our new paper on the Fermi bubbles: Guo & Mathews 2011b, submitted to ApJ http://arxiv.org/abs/1103.0055