How AGN Jets Heat the Intracluster Medium

Hsiang-Yi Karen Yang
Einstein Fellow
University of Maryland and JSI
Einstein Symposium, Oct. 19, 2016

(astro-ph://1605.01725)
Perseus cluster (Fabian+ 2010)
AGN Feedback

- Radio bubbles
- $P_{\text{cav}} \sim L_{\text{cool}}$

Courtesy of J.Hlavacek-Larrondo
Success of AGN simulations

- Hydrodynamic
- Cold gas accretion
- Momentum-driven Jets

Gaspari+ (2011, 2012)
Li+ (2014, 2015)
How AGN jets heat the ICM?

- Possible heating mechanisms:
  - Cavity heating (Churazov+ 2001)
  - Weak shocks (Fabian+ 2003)
  - Sound waves (Fabian+ 2005)
  - Turbulence dissipation (Zhuravleva+ 2014)
  - Mixing with hot bubble gas (Hillel+ 2016)
  - Cosmic-ray heating (Guo+ 2008, Pfrommer+2013)

How to distribute heat radially and isotropically?

Which mechanisms are dominant?
How AGN jets heat the ICM?

**Statement 1:** Shock heating is enough to balance radiative cooling (Randall+ 2015)

**Statement 2:** Bubble mixing is more efficient than shock heating (Hillel+ 2016)

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**Fig. 2.** Left: Exposure corrected, background subtracted, 0.3–3 keV Chandra image, with point sources removed and smoothed with a $\sigma=1.500$ Gaussian. The image shows bright rims surrounding an inner pair of cavities, a prominent elliptical edge surrounding a pair of cavities at intermediate radii (with the more obvious cavity to the SW and the NE cavity apparently broken into two connected cavities), and a subtle outer edge associated with a faint pair of outer cavities (with the more obvious cavity to the NE). Right: X-ray image divided by a 2D fitted beta model and smoothed with a $\sigma=600$ Gaussian, shown on the same scale. The outer cavities and edges are more clearly seen in this residual image, while the inner cavities are not visible due to the larger smoothing scale and saturation of the color scale. The image also reveals a faint “channel” of decreased surface brightness extending to the north, apparently connected to the NE outer cavity.

**Fig. 3.** Left: Background and exposure corrected 0.4–7.2 keV XMM-Newton image of N5813. Right: Smoothed Chandra image shown on the same scale, with the intensity scale chosen to better show the faint, outer emission.

**Fig. 5.** The energy history of different traced regions of the simulation studied here. In the left panel we present the evolution with time of three energy components of the ICM gas that starts before the jets become active at $t=0$ inside an eighth of a ball with $r=15$ kpc centered at the origin. It is an eighth of a ball as we simulate one eighth of the space. The green (upper) line represents the internal energy, the blue (middle) line represents the kinetic energy, and the red (lower) line represents the gravitational energy of this traced gas. The middle panel shows the energy histories of the torus shown in Fig. 3, and the right panel shows the energy histories of the torus shown in Fig. 4. All energies are shown relative to their values at $t=0$. The initial internal energies $E_{\text{in}}(0)$ of the traced regions, from the left panel to the right, are $3.1 \times 10^{58}$ erg, $5.5 \times 10^{57}$ erg and $1.1 \times 10^{58}$ erg, respectively. The left and middle panels are cut off at the time when the traced material starts leaving the grid.
How AGN jets heat the ICM?

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How to distribute heat radially and isotropically?

Which mechanisms are dominant?

Goal – Gain insights from hydro simulations of self-regulated AGN feedback!
Density

Temperature  $t = 3.000 \text{ Gyr}$

Projected X-ray Emissivity

Jet Mass Fraction

Jet cones

Ambient region
Turbulence dissipation -> Not likely

- Turbulent energy ~few percent of thermal energy (Hitomi 2016)
- Turbulent energy only ~1% of injected AGN energy (Reynolds+ 2015)
Passive tracers – the Lagrangian view

\[ K \equiv \frac{T}{n_e^{2/3}} \]

\[ \frac{dK}{dt} = H - C \]

- **Heating done by bubble mixing and shocks**
- **Mixing more efficient, but shocks more frequent**
- **Net cooling in amb. region; net heating in jet cones**
Static tracers – the Eulerian view

- Hydro variables are remarkably constant!
Within jet cones:
- **Net heating by bubble mixing and shocks**
- **But T does not increase!?!**

Within ambient region:
- **Net cooling**
- **But T does not decrease!?!**
Gas internal energy equation:

\[
\frac{\partial e_i}{\partial t} + \nabla \cdot (e_i \vec{v}) + P(\nabla \cdot \vec{v}) = H - C
\]

- Change of \( e_i \) at a fixed location: \( \approx 0 \)
- Transport by advection or convection
- Adiabatic compression or expansion

Transport & adiabatic processes important!!
\[ \varepsilon_\alpha \rightarrow \left[ \frac{\partial e_i}{\partial t} + \nabla \cdot (e_i \vec{v}) + P(\nabla \cdot \vec{v}) = H_{\text{mix}} + H_{\text{sh}} - C \right] \]

\[ \alpha \in \{ \text{transport, adiabatic, mixing, shocks, cooling} \} \]

\[ \Rightarrow \varepsilon_{\alpha,i} = \frac{\int \varepsilon_\alpha \, dV}{V_i} \]

\[ \Rightarrow <\varepsilon_{\alpha,i}>_t \]
From shocks within the cooling radius. For the ambient mixing contributes about twice the amount of heating

Since instead of radiative cooling, heating from bubble

0

(kpc), we find that within the jet cones, a non-negligible amount of jet materials within the inner radial bins in the upper right panel of Figure 11, there a part of gentle circulation. Note that for the first two by adiabatic compression as it flows inward radially as from already-heated gas. The gas further gains energy though having net cooling, is pumped by flows of energy

through the surfaces of each sector, we find that the en-

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By estimating the amount of advective energy transfer to different processes, we find that within the jet cones (left column) and the ambient region (right column). Data marked with open squares represent processes that are cooling for a

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\begin{align*}
  \text{Jet} &\quad \text{cones} \\
  \text{Jet} &\quad \text{mixing (inferred)} \\
  \text{Transport} &\quad + \text{Adiabatic} \\
  \text{Shock heating} &
\end{align*}
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![Image of NGC 5813 with labeled regions: Northern Cavity, NE Outer Cavity, Outer Edge, SW Outer Cavity, Outer Edge.]

![Graph showing energy history with time in Myr and energy in ergs, with three lines representing internal, kinetic, and gravitational energy components.]

AND
from shocks within the cooling radius. For the ambient processes instead of radiative cooling; heating from bubble $0_{\text{kpc}}$), we find that within the jet cones, it appears to be some net energy losses. This loss of internal energy primarily flows from the interface between the jet cones and the ambient region, as opposed to radial inflow through the surfaces of each sector, we find that the energy is pumped by flows of energy. With net cooling, this scenario is consistent with the fact that there is rough balance between heating and cooling (see Figure 2).

Fig. 11.—Time-averaged (between 1 and 3 Gyr) radial profiles of heating and cooling emissivities in units of $\text{erg s}^{-1} \text{cm}^{-3}$. The top panels show the contributions from radiative cooling, shock heating, and transport plus adiabatic processes. The bottom panels show the contributions from turbulence and waves, which are decomposed into different processes: radiative cooling, shock heating, transport + adiabatic processes, and turbulent heating. The energy associated with turbulence is always only a minor portion. This is consistent with the energy partitions inferred by recent analysis of the Perseus cluster (Zhuravleva et al. 2016). The total kinetic energies within the bubble are considered to be associated with the tracer particles, whereas the energy associated with shocks contains a non-negligible amount of jet materials within the inner 10 kpc for regions containing the bubbles (Yang & Reynolds 2015; Reynolds et al. 2015). The total kinetic energies within the bubble can be decomposed into different energy terms: turbulence, shock heating, and transport + adiabatic processes. All energetics suggest that in our simulation, most internal energy comes from turbulence but also from shocks and waves. In Section 3.2, we showed that the kinetic energy associated with turbulence is about 17%, while the rest of gas internal energy comes from advection and adiabatic compression. The over-density and wave mode components (Yang & Reynolds 2015; Yang et al. 2013) are considered to be associated with the tracer particles.
In Section 3.2, we showed that the kinetic energy as-
Within jet cones:
- **Net heating** by bubble mixing and shocks
- But *T does not increase* due to adiabatic expansion

Within ambient region:
- **Net cooling**
- But *T does not decrease* due to advection & adiabatic compression
A model of ``gentle circulation"
Summary -- How AGN Jets heat the ICM?

- **What mechanisms are dominant?**
  - Heating done by *bubble mixing* and *weak shocks*
  - *Turbulent heating* is not dominant

- **How to distribute heat radially and isotropically?**
  - Heating and cooling profiles do **not** need to balance
  - AGN jets do **not** need to heat isotropically
  - ICM undergoes "**gentle circulation**" that transports and compensates AGN heating