Heating & cooling cycles in cool cluster cores

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COOL CORE CYCLES: COLD GAS AND AGN JET FEEDBACK IN CLUSTER CORES

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Cold gas condensation

- allows feedback to act sufficiently fast, unlike Bondi
- $t_{\text{cool}}/t_{\text{ff}} \sim$ threshold around 10 seems robust (at least in sims)
- cooling & heating cycles
- push $\epsilon$ to smallest allowed by observations
- cold gas inflows & outflows
- angular momentum: stochastic cold accretion
AGN jet-ICM sims.

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p - \rho \nabla \Phi + S_\rho v_{\text{jet}} \hat{\mathbf{r}}
\]

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_\rho
\]

\[
\frac{p}{\gamma - 1} \frac{d}{dt} \ln \left( \frac{p}{\rho^\gamma} \right) = -n^2 \Lambda
\]

source terms to mimic injection by feedback AGN jets
AGN jet-ICM sims.

\[
\begin{align*}
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) &= -\nabla p - \rho \nabla \Phi + S_\rho v_{\text{jet}} \hat{r} \\
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} &= S_\rho \\
\frac{p}{\gamma - 1} \frac{d}{dt} \ln\left( \frac{p}{\rho^\gamma} \right) &= -n^2 \Lambda
\end{align*}
\]

Source term applied in a small bipolar cone at the center: opening angle of 30°, size 2 kpc

\[\dot{M}_{\text{jet}} v_{\text{jet}}^2 = \epsilon \dot{M}_{\text{acc}} c^2\]

\(v_{\text{jet}} = 0.1c, \ \epsilon = 6 \times 10^{-5}, \ r_{\text{in, out}} = 1, \ 200 \ \text{kpc}\)

robust to variations
Dependence on halo mass & efficiency

larger $\epsilon$ suppresses accretion

more massive halos require larger $\epsilon$

depends on where $\dot{M}$ calculated

$1.8 \times 10^{15} \, M_{\odot}$

$7 \times 10^{14} \, M_{\odot}$
Density movie

BCG+NFW in PLUTO
256x128x32 in (logr,θ,φ)

\[ r_{\text{min}}=0.5 \text{ kpc}, \quad r_{\text{max}}=0.5 \text{ Mpc} \]

evolution for \(~2.8 \text{ Gyr}\)

made by Deovrat Prasad
Figure 1. Pressure (upper panel), electron number density (middle panel), and temperature (lower panel) contour plots (R–z plane at $\theta_f$) in the core at different times for the 3D fiducial run. The density is cutoff at the maximum and the minimum contour level shown. The low-density bubbles/cavities are not symmetric and there are signatures of mixing in the core. The left panel corresponds to a time just before a cooling time in the core. The second panel from the left shows cold gas dredged up by the outgoing jets. The rightmost panel shows infalling extended cold clouds. The pressure maps show the weak outer shock, but the bubbles/cavities so prominent in the density/temperature plot are indiscernible in the pressure map, implying that the bubbles are in pressure equilibrium and buoyant. Also notice the outward-propagating sound waves in the two middle pressure panels in which the jet is active. The infalling/rotationally supported cold gas has a much lower temperature and pressure than the hot phase. The arrows in the temperature plots denote the projected gas velocity unit vectors.
Figure 1. Pressure (upper panel), electron number density (middle panel), and temperature (lower panel) contour plots (R–z plane at $t_f$) in the core at different times for the 3D fiducial run. The density is cutoff at the maximum and the minimum contour level shown. The low-density bubbles/cavities are not symmetric and there are signatures of mixing in the core. The left panel corresponds to a time just before a cooling time in the core. The second panel from the left shows cold gas dredged up by the outgoing jets. The rightmost panel shows infalling extended cold clouds. The pressure maps show the weak outer shock, but the bubbles/cavities so prominent in the density/temperature plot are indiscernible in the pressure map, implying that the bubbles are in pressure equilibrium and buoyant. Also notice the outward-propagating sound waves in the two middle pressure panels in which the jet is active. The infalling/rotationally supported cold gas has a much lower temperature and pressure than the hot phase. The arrows in the temperature plots denote the projected gas velocity unit vectors.


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infalling cold gas condenses when the jets are weak!
The Astrophysical Journal, cycles, we show in Figure prominent in the temperature pro quantities because of dropout and adiabatic cooling. Temperatures are rather modest compared to entropy measured at 20 kpc and spread about it are shown. The median is calculated for the density increases and observations. 1 Gyr is peaked toward the center, indicating that the cluster radius are shown in gray. The spread in quantities outside the core is in a cooling phase. The spikes in density at 3 Gyr have overheating K keV + fi X-ray emissivity-weighted flows and mixing shows a general increase with radius, as seen in les with entropy within one standard deviation at the same fi 10 kpc is quite small, but les of important thermodynamic quantities for which the entropy at 20 kpc is within fi 20 keV cm tt ∼ 23 fi 14 keV cm tt 1 Gyr. On the other hand, the fi 2008 fourth panel; see also Revaz et al. turbulence in the ICM at large fi 1D pro tt – 10 kpc is peaked toward the center because multiphase cooling decreases fi 20 kpc is within fi Tn 811:108 – 623, our cold torus is dynamic in nature as AGN jets disrupt it time and again, but it reforms due to cooling. Figure shows the zoomed-in density snapshots in the fi 3.1.3. The Cold Torus first active AGN phase. At fi 10 kpc – 623, the median pro fi 2008 rough the core size fi 10 kpc = 23 fi 10 kpc = 811:108 and strong jet feedback simultaneously, fi 23 fi 7 shows the evolution of the torus at various fi 10 kpc = 23 fi 10 kpc = 811:108 and can also condense out of the ICM at large scales. As the cluster evolves in the form of an angular-momentum supported cold gas torus rotates in a clockwise sense, essentially because the hot gas out of which it condenses are mainly responsible for heating the cluster core. These backflows and mixing fi 10 kpc = 23 fi 10 kpc = 811:108 are important in the cluster center at 0.5 Gyr. Small cold gas clouds are shown in different panels of entropy at 20 kpc are calculated. Various pro fi 10 kpc = 23 fi 10 kpc = 811:108 fi 10 kpc = 23 fi 10 kpc = 811:108 correspond to the median entropy at 20 kpc. While Figure fi 10 kpc = 23 fi 10 kpc = 811:108 shows the detailed kinematics of cold gas and jet fi 10 kpc = 23 fi 10 kpc = 811:108 fluctuations in other pro fi 10 kpc = 23 fi 10 kpc = 811:108 shows the projection of velocity unit vectors. As the cluster evolves fi 10 kpc = 23 fi 10 kpc = 811:108 time and again, but it reforms due to cooling.
density reasonable
Cold rotating torus

Fig. 3.—The 2-D (z = 0) contour plot of density in the inner region at different times for the fiducial 3-D run, with the projection of the velocity unit-vector represented by arrows. The top-left panel shows the beginning of the infall of cold gas with random angular momentum. The top-middle panel shows an anti-clockwise transient torus. All times after this show a clockwise torus which waxes and wanes because of cooling and AGN heating cycles. Even at late times the cold torus is not stable and gets disrupted by jets. It reforms over a few cooling times. Figure 3 shows the evolution of the torus at various stages of the simulation.

The top-left panel of Figure 3 shows the cluster center at 0.5 Gyr. Small cold gas clouds are accumulating in the core after the first active AGN phase. At 1.3 Gyr, cold gas accreting through the inner boundary has an anti-clockwise rotational sense. At 1.98 Gyr, cold gas (and the hot gas out of which it condenses) is rotating clockwise. Jet activity leading up to this phase has reversed the azimuthal velocity of the cold gas. At all times after this the dynamic cold gas torus rotates in a clockwise sense, essentially because the mass (and angular momentum) in the rotating torus is much larger than the newly condensing cold gas.

The middle panels of Figure 3 show the dynamic nature of the rotationally supported torus. The torus gets disrupted due to jet activity as seen in the middle panel of Figure 3, but forms again quickly. The snapshots at 2.4 and 2.45 Gyr show that the inner region is covered by the very hot/dilute jet material. This unphysical behavior is mainly because of our feedback prescription; we scale the jet power with the instantaneous mass inflow rate through the inner boundary (see Eq. 6). Even small oscillations of the cold torus can sometimes lead to a large instantaneous mass inflow through the inner boundary and hence an explosive jet feedback in which the jet material encompasses the inner core. The reassuring fact is that these explosive 'events' are rare and the jet material is quickly mixed with the ICM, and the core settles back to a quiescent state (see the top panel of Fig. 9 which shows a large peak in jet energy at 2.4 Gyr). In reality, the cold gas in the torus is mainly consumed by star-formation and only a part of it reaches the SMBH, and that too at the slow viscous timescale. In addition, the rapidly reorienting AGN jets can disrupt the massive cold torus (e.g., see Babul et al. 2012). Li & Bryan (2014b) show that after 3 Gyr the cold gas settles down in form of a stable torus, with no further condensation of extended cold gas. This is inconsistent with observations. The bottom panels in Figure 3 from our fiducial run shows that the torus is unsteady even at late times. Moreover, unlike them, we see extended cold gas condensing out till the end. We compare our results in detail with Li & Bryan (2014b) in section 4.1.

To test the role of cooling in maintaining the cold rotating torus, we restarted the 3-D fiducial run after a massive cold torus had formed (3 Gyr), and re-ran it without radiative cooling or feedback heating. While the cold torus is long-lived even without cooling (Kelvin-Helmholtz instability does not grow for at least the next Gyr), it is heated (by numerical dissipation) to $10^5$ K, and is no longer maintained at the temperature of the stable phase ($10^4$ K). Thus, radiative cooling function is what dictates the temperature of the cold phase. The few kpc scale molecular torus
Cold torus in Hydra A

Figure 2. This figure shows the IFU maps of the Hα emission as taken from fits to the Hα/[NII] triplet observed in the VIMOS cubes.

Panel (A) shows a continuum image made by collapsing the cube, the contours show the Hα emission clearly centred on the BCG. Panel (B) is a Hα Flux map which shows a disc of bright emission running across the BCG. In panel (C) we show the relative velocity of the Hα line to the galaxy redshift, a strong velocity gradient of \( \sim 600 \text{ km s}^{-1} \) can clearly be seen. Contoured on this plot are lines of constant velocity created by fitting a disc model to the velocity map. The final panel (D) shows the measured Full Width Half Maximum (FWHM) of the line which can be seen to broaden at the centre of the velocity gradient.

This is likely to be due to the lower signal–to-noise as the lines are present within the total spectrum of this region (extracted \( 1 \times 1 \text{ arcsec}^2 \) centred on the offset Paα peak) though the line is weak compared to Paα.

[FeII] emission was the only line detected in the H-band observations. The maps presented in Figure 5 show that the [FeII] emission is compact and located at the centre of the BCG. The luminosity of [FeII] emission has a high dependence on the gas density (Bautista et al. 1994) so we would expect it to be brightest in the central regions where the gas density is higher. Despite being compact the line does appear to be extended to the east on scales slightly greater than the seeing. Within this small extent there appears to be a velocity change of \( \sim 200 \text{ km s}^{-1} \) across the emission. This is more examples from ALMA, Hershel? may be SF doesn’t let a massive torus form ~5 kpc cold torus
Jets & fast outflows

is there any relation between jets and cold gas kinematics?

jet power highly time variable
Jets & fast outflows

AGN Jets as source of fast outflows

Jet power ($10^{41}$ erg s$^{-1}$)

Outflow, 5 kpc ($M_\odot$ yr$^{-1}$)

cold outflows generally coincide with sudden rise in jet power
Jets & fast outflows

Jet power \(10^{41}\) erg s\(^{-1}\)
Outflow, 5 kpc \(M_\odot\) yr\(^{-1}\)
Inflow, 5 kpc \(M_\odot\) yr\(^{-1}\)

2.2 Gyr
2.4 Gyr

cold inflows when jet power wanes
Snapshots of inflow/outflow phases
radially-dominant component

fast outflows during jet rise
slow infall at most times
Cold gas observations

$10^{10}$ Msun of molecular gas

A1664 [Russell et al. 2014]

low (200 km/s) and high (600 km/s) velocity components
AGN feedback cycles

core cooling
↓
large cold accretion onto SMBH
↓
negative FB, heating wins over cooling, energy pumped back in ICM
↓
after few cooling times avg. thermal balance in core
↓
cold, multiphase gas condenses if \( t_{\text{cool}}/t_{\text{ff}} \leq 10 \)

cooling & AGN jet heating cycles in cool-core clusters
Cycles in sims.

“phase space” of jet power cold gas mass vs. hot gas properties
Huge scatter in sims.

cold accretion does not show tight correlations!

consequence of chaotic cycles!
Observations of cycles

[McDonald et al. 2011]

Observations of “phase space”

Decoupled from feedback
AGN Outburst

M $\sim 10^{14.5} \, M_\odot$
M $\sim 10^{14} \, M_\odot$
M $\sim 10^{13} \, M_\odot$

Feedback loop closed

hot
cold

log ($L_{0.5-2 \, \text{keV}}/10^{41} \, \text{erg s}^{-1}$)

L_{1.4 \, \text{GHz}} \times 10^{24} \, \text{W Hz}^{-1}$
hot accretion inadequate

\[ \dot{M}_{\text{BH}} \lesssim 0.01 \dot{M}_{\text{Bondi}} \]

only a small fraction makes it to SMBH because of outflows

Bondi resolved in Sgr A*, M 87, NGC 3115: all show suppression
Angular momentum problem

t_{\text{visc}} \sim \frac{1}{\alpha (H/R)^2 \Omega_K}

t_{\text{visc}} \sim 4.7 \text{ Gyr} \left( \frac{R}{1 \text{ pc}} \right)^{3/2} \left( \frac{H/R}{0.001} \right)^{-2} \left( \frac{\alpha}{0.01} \right)^{-1}

too long if H/R \sim 10^{-3}, of standard AGN thin disks
moreover, star formation where M_d/M_{BH} exceeds H/R

must avoid a large thin disk
$t_{\text{visc}} < \text{ core cooling time}$
Key issues

- microscopic dissipation: turbulent mixing/heating, shocks, CRs
- conduction, hot accretion secondary
- from 1 kpc to << 1 pc (BH sphere of influence): core to BH accretion
- stochastic cold gas, angular momentum barrier, most cold gas consumed by SF
- relation to radio mini-halos
- spiral structures, cold fronts, sloshing

Thanks!
turbulent velocities
structure of hot gas vs halo mass

[Sharma et al. 2012]