Cool-Core Cycles and Phoenix

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ABSTRACT
Recent observations show that the star formation rate (SFR) in the Phoenix cluster’s central galaxy is \( \sim 500 \, M_\odot \, \text{yr}^{-1} \). Even though Phoenix is a massive cluster (\( M_{200} \approx 2.0 \times 10^{15} \, M_\odot \); \( z \approx 0.6 \)) such a high central SFR is not expected in a scenario in which feedback from an active galactic nucleus (AGN) maintains the intracluster medium (ICM) in a state of rough thermal balance. It has been argued that either AGN feedback saturates in very massive clusters or the central supermassive black hole (SMBH) is too small to produce enough kinetic feedback and hence is unable to quench the catastrophic cooling. In this work, we present an alternate scenario wherein intense short-lived cooling and star formation phases followed by strong AGN outbursts are part of the AGN feedback loop. Using results from a 3D hydrodynamic simulation of a standard cool-core cluster (\( M_{200} \sim 7 \times 10^{14} \, M_\odot ; \ z \approx 0 \)), scaled to account for differences in mass and redshift, we argue that Phoenix is at the end of a cooling phase in which an AGN outburst has begun but has not yet arrested core cooling. This state of high cooling rate and star formation is expected to last for \( \lesssim 100 \, \text{Myr} \) in Phoenix.

Key words: Galaxy Clusters, Cooling flow, Black Hole, AGN feedback, Intra-cluster medium

1 INTRODUCTION
Recent deep multi-wavelength observations of the Phoenix cluster by McDonald et al. (2014, 2019a,b) have detected a star formation rate of \( \sim 500 \, M_\odot \, \text{yr}^{-1} \) in the central galaxy (\( r < 50 \, \text{kpc} \)). Such a high star formation rate is not expected in the standard AGN feedback scenario, even in a massive galaxy cluster like Phoenix (\( M_{200} \approx 1.8 \times 10^{15} \, M_\odot \)). However, it is consistent with the condensation rate of a pure cooling flow in the intracluster medium (ICM). Phoenix is therefore unlike CL09104, another massive galaxy cluster in which the high star formation rate (70–200 \( M_\odot \, \text{yr}^{-1} \)) is due to an ongoing merger (O’Sullivan et al. 2012). Given that the cooling time, \( t_{\text{cool}} = 3n_kT/[2n_e \eta_i \Lambda] \), in the central \( r < 20 \, \text{kpc} \) of Phoenix is an order of magnitude shorter than in any other observed galaxy cluster, McDonald et al. (2019a) have speculated that Phoenix has experienced an evolutionary pathway different from other cool core clusters.

The intracluster medium (ICM) is expected to become multiphase whenever \( \min(t_{\text{cool}}/t_\text{ff}) \lesssim 10 \) (with \( t_\text{ff} = \sqrt{\frac{\Omega}{G}} \)), leading to star formation and AGN outbursts (McCourt et al. 2012; Sharma et al. 2012; Prasad et al. 2015). Most cool core clusters are observed to be in a state of rough thermal balance, with \( \min(t_{\text{cool}}/t_\text{ff}) \) between 10–20 (Voit et al. 2015a,b; Hogan et al. 2017; Pulido et al. 2018). Few have \( t_{\text{cool}}/t_\text{ff} < 10 \), but Phoenix has \( t_{\text{cool}}/t_\text{ff} \sim 1 \) at \( r = 3 \, \text{kpc} \) (McDonald et al. 2019a). None with \( t_{\text{cool}}/t_\text{ff} \lesssim 5 \) were previously known, making Phoenix a significant outlier.

Phoenix has a large X-ray luminosity (\( \approx 4.7 \times 10^{45} \, \text{erg s}^{-1} \); Ueda et al. 2013) and a kinetic feedback power \( \sim 10^{46} \, \text{erg s}^{-1} \) inferred from the cavities the AGN has produced, assuming the AGN has shut off and the cavities are rising buoyantly (Russell et al. 2017; McDonald et al. 2019a). The cavity power is therefore comparable to the X-ray luminosity, but it has been argued that the mechanical jet power may be saturated and unable to quench the cooling flow, perhaps because of a central black hole mass that is small compared to the halo mass (McDonald et al. 2019a).

In this work, we argue that Phoenix is not fundamentally different from other cool-core clusters and does not necessarily represent a failure of kinetic SMBH feedback. We suspect instead that Phoenix is near the end of a short-lived cooling state, with AGN feedback just turning back on after a \( \ll 1 \, \text{Gyr} \) starburst\(^1\). Given that the fraction of young

\(^1\) Note added during pre-publication: The age of the cavities in
stellar population is small, the current starburst cannot be
long lived. Similar events occur in the fiducial simulation
of Prasad et al. (2018), in which a strong AGN outburst fol-
follows each phase of core cooling. This transitional state
lasts for only \( \sim 50 - 100 \) Myr, after which the AGN heats
and disperses the core to a state more typical of cool core
clusters. In simulations, such cooling phases are seen across
a range of halo masses but are most frequent in the most
massive halos, given a fixed efficiency for converting mass
accretion into kinetic feedback power (Prasad et al. 2015;
Li et al. 2015; Prasad et al. 2018). Cooling phases are more
frequent in very massive halos because even strong feedback
is unable to push low-entropy gas far from the center.

2 COOLING AND INITIAL AGN HEATING PHASE

In the simulation discussed here, the ICM was initialised in
hydrostatic equilibrium in a gravitational potential given by
the sum of a Navarro-Frenk-White (NFW) potential for the
dark matter halo and a singular isothermal sphere (SIS) poten-
tial for the central brightest cluster galaxy (BCG). The
fiducial run initially has \( \min (t_{\text{cool}}/t_{\text{ff}}) \approx 7 \) at \( r \approx 10 \) kpc and a
minimum cooling time \( \approx 200 \) Myr. An accretion rate \( (M_{\text{acc}}) \)
calculated at 0.5 kpc determines the power \( \epsilon M_{\text{acc}} c^2 \) of bipo-
lar jets of kinetic feedback injected at small radii (for details
see Prasad et al. 2015, 2018). Accretion and jet injection
are minimal at first because the galaxy cluster is initialized
in hydrostatic equilibrium. After a core cooling time \( (\sim 200
\) Myr) the cooling-flow accretion rate rises, resulting in en-
hanced AGN jet power. AGN outbursts then heat the core,
push gas around, and raise \( t_{\text{cool}}/t_{\text{ff}} \), keeping the average \( M_{\text{acc}}
\) well below the cooling-flow value. Throughout its lifetime,
the cool core undergoes multiple radiative cooling and AGN
heating cycles.

Figure 1 shows density (left panels) and temperature
(right panels) slices along the jet axis during a cooling phase
at \( t = 2.62 \) Gyr (top panels) and the subsequent AGN out-
burst at \( t = 2.64 \) Gyr (bottom panels). Those epochs corre-
spond to a strong starburst before AGN feedback couples to
the ICM and quenches star formation (see the right panel in
Fig. 4 of Prasad et al. 2018).

Figure 2 shows projected surface brightness maps of the
X-ray gas (0.5-10 keV) at the same two epochs as Figure 1.
During the cooling phase the X-ray surface brightness is
relatively smooth within \( r \approx 10 \) kpc (upper panel). But as AGN
jets begin to make their way out of the core, pronounced
surface brightness features appear in the form of bright rings
around the jet-driven cavities (lower panel).

Morphologically, Phoenix appears to be in a state simi-
lar to the \( t = 2.64 \) Gyr snapshots (compare our Figs. 1 & 2
with Figs. 1, 2, and 5 in McDonald et al. 2019a). Current star
formation, as traced by UV and [OII], appears enhanced at
the periphery of the X-ray cavity created by the AGN out-
burst. The bipolar X-ray cavities observed in Phoenix are
attached to the center and have a major axis of \( \sim 25 \) kpc,

\( \text{Phoenix} \) from the latest observations is estimated to be \(< 10 \) Myr
\(^2\) The 3D hydrodynamic NFW+BCG run without stellar deple-
tion.

Figure 1. Electron number density \( (n_e) \) in \( \text{cm}^{-3} \) (upper panels)
and temperature \( (T) \) in keV (lower panels) in \( 60 \) kpc \times \( 60 \) kpc
slices within the plane of jet injection. Two epochs are shown,
one near the end of the cooling phase (at \( 2.62 \) Gyr, top panels)
and the other at the beginning of the AGN outburst phase (at
\( 2.64 \) Gyr, bottom panels). The cooling phase exhibits filamentary
structures condensing out in the core \( (r \lesssim 30 \) kpc\). During the
initial AGN outburst phase, high density shocked regions can be
seen around the cavities inflated by AGN jets.

3 THERMODYNAMIC PROFILES

\( \text{Phoenix} \) exhibits profiles of entropy, cooling time, and \( t_{\text{cool}}/t_{\text{ff}} \)
in its core, \( r < 0.02 \times r_{200} \) (\( \sim 50 \) kpc), that are unique com-
pared to any other observed cluster. However, a comparison
of the Phoenix cluster’s scaled\(^3\) thermodynamic profiles with
those from our simulation at epochs corresponding to the
transitions between cooling and AGN outburst phases in
our fiducial run reveals close similarities.

The top left panel in Figure 3 shows the azimuthally-
averaged, emissivity-weighted scaled entropy profile (Voit
et al. 2005; McCarthy et al. 2008; Kaiser 1986) of X-ray
gas (0.5-10 keV) for two different Phoenix-like cooling cy-
cles, the \( t = 1.85 - 2.0 \) Gyr (red lines) and the \( t = 2.55 - 2.7 \)
Gyr cycles (blue lines). The solid lines show the entropy pro-
diles during the cooling phase and the dot-dashed lines show

\( ^3 \) We assume WMAP9 (Bennett et al. 2013) cosmology to com-
pute the characteristic parameters used to rescale the profiles.
The scaled emissivity-weighted temperature plot (top right panel, Figure 3) shows that the temperature profile of Phoenix over the radial range $r < 0.1 r_{200}$ is likewise consistent with the cooling phase of our simulated cool core cluster during the second cycle. The individual wiggles in the temperature profile are due the presence of AGN cavities.

The bottom right panel in Figure 3 shows the scaled $t_{\text{cool}}/t_{\text{ff}}$ profiles from our simulation. Before the AGN turns on, $t_{\text{cool}}/t_{\text{ff}}$ reaches its minimum value of 0.01 at $r_{\text{cool}}/r_{200}$ ($\sim 2 - 3$) at $r \sim 0.002 r_{200}$ ($\sim 5$ kpc) and rises approximately linearly toward larger radii. Phoenix similarly exhibits an approximately linear rise in $t_{\text{cool}}/t_{\text{ff}}$ from 0.001 at $r_{200}$ ($\sim 2 - 3$ kpc) out to large radii. The simulation and Phoenix scaled profiles are in excellent agreement.

Figure 4 shows how the (unscaled) $t_{\text{cool}}/t_{\text{ff}}$ profile from our simulation varies during a 150 Myr period that includes the intense cooling and the subsequent AGN outburst phases at $t = 2.55 - 2.7$ Gyr. Line colours represent time as shown in the colour bar. During the initial cooling phase, $t_{\text{cool}}/t_{\text{ff}}$ declines in the central $r < 30$ kpc, and the plasma becomes unstable to multiphase condensation, producing cold gas clumps that raise the core density and fuel a strong AGN outburst. These profiles show the first signs of AGN heating at $2.64$ Gyr within $r < 3$ kpc. At $2.65$ Gyr the effect of AGN heating can be seen extending to $r < 10$ kpc, although min$(t_{\text{cool}}/t_{\text{ff}})$ is still $\approx 5$. By $2.68$ Gyr, the AGN outburst has driven the core to min$(t_{\text{cool}}/t_{\text{ff}}) \approx 10$, and has driven it to $\sim 20$ by $2.7$ Gyr. The figure shows that min$(t_{\text{cool}}/t_{\text{ff}})$ is maintained for the first $\sim 20$ Myr of the active AGN phase. Similar behaviour is seen towards the end of an earlier cooling cycle at $t = 1.85 - 2.0$ Gyr (see Fig. 3, as well as the right panel of Fig. 4 in Prasad et al. 2018).

During the $t = 1.85 - 2.0$ Gyr cycle, the cooling rate in the central $10$ kpc is $\sim 200 \ M_\odot \ yr^{-1}$ (about a third of the steady cooling flow rate), leading to accumulation of $\gtrsim 5 \times 10^8 \ M_\odot$ of cold gas ($T < 10^4$ K) by $1.95$ Gyr. The cooling rate dies down after this as the jets heat up the core, partly evaporating the cold gas leading to a slight decrease in the total cold gas. During the second cooling cycle at $t = 2.55 - 2.7$ Gyr, we observe a similar behaviour as well as enhanced cooling mostly along the periphery of the cavities at $2.62$-$2.66$ Gyr as the jet cavities inflated. The latter leads to an accumulation of $\sim 2 \times 10^9 \ M_\odot$ of cold gas ($T < 10^4$ K) and a dropout of $> 10^8 \ M_\odot$ of intermediate temperature ($10^4 K < T < 5 \times 10^5$) gas. This is an example of positive feedback (Combes 2017). Cold gas mass starts to decline after $2.66$ Gyr as the shocks and mixing gradually heat up the core.

For comparison, Figure 3 also shows the scaled profiles (magenta solid lines) for a steady cooling flow applied to the mass model of Phoenix ($M_{200} = 2.5 \times 10^{15} M_\odot$, $C_{200} = 10$, $V_c = 250 \ km \ s^{-1}$) and appropriate boundary conditions at $500 \ kpc$ ($n_e = 10^{-3} \ cm^{-3}$, $K = 1057 \ keV \ cm^2$). The steady cooling flow model is similar to the observed profiles (McDonald et al. 2019a; see also Stern et al. 2019) but so are the profiles from our simulations (once the mass and redshift differences are taken into account) with feedback in the cooling phase. Thus, similarity to a cooling flow solution does not necessarily imply an absence of feedback heating.
4 OBSERVATIONAL AND THEORETICAL LIMITATIONS

While the similarities between Phoenix and the cooling phases of our simulated cluster are encouraging, observations of other cool core clusters show that few have $1 \lesssim \min(t_{\text{cool}}/t_{\text{ff}}) \lesssim 10$. However, the temporal distribution of $\min(t_{\text{cool}}/t_{\text{ff}})$ in our simulation (see Figure 11 of Prasad et al. 2018) suggests that systems with $\min(t_{\text{cool}}/t_{\text{ff}}) \lesssim 5$ should be present.

One possibility is that Phoenix-like cooling episodes are more common in our idealized non-cosmological simulations than in real clusters. For example, our idealized simulations do not include cosmological structure formation, which can produce dynamical perturbations capable of promoting multiphase condensation at higher levels of $t_{\text{cool}}/t_{\text{ff}}$ (Choudhury et al. 2019), preventing lower levels from being reached. Consequently, the temporal distribution of $\min(t_{\text{cool}}/t_{\text{ff}})$ for a single, idealized, non-cosmological simulated cluster might not be representative of a heterogenous cluster population with very different accretion histories. Additionally, our simulations (Prasad et al. 2018) do not include magnetic fields or anisotropic thermal conduction, which may also lower the incidence of very small $t_{\text{cool}}/t_{\text{ff}}$. All of the above effects will result in less Phoenix-like states than in our simulations.

Another possibility is that low values of $\min(t_{\text{cool}}/t_{\text{ff}})$ like the one observed in Phoenix can be detected only in deep observations that provide a large enough photon count at $r < 10$ kpc. In McDonald et al. (2019a), the large photon count allowed accurate removal of the AGN X-ray point source, revealing sharply peaked diffuse emission indicative of unusually low entropy gas. Earlier observations without accurate point-source removal estimated the central temperature of Phoenix to be $\approx 7$ keV and the central entropy to be $> 10$ keV cm$^2$ (see Phoenix [SPT-CLJ2344-4243] in Figs. 3, 5 of McDonald et al. 2019b), significantly greater than the values obtained by McDonald et al. 2019a.

A greater photon count also enables more finely grained radial binning, which improves the spatial resolution achievable with deprojection. Figure 5 tries to quantify the effects of spatial resolution on observational estimates of $\min(t_{\text{cool}}/t_{\text{ff}})$. It shows how $\min(t_{\text{cool}}/t_{\text{ff}})$ varies with time in our fiducial simulation for different inner cut-off radii. The dot-dashed magenta line shows $\min(t_{\text{cool}}/t_{\text{ff}})$ for $r > 10$ kpc, the dashed black line for $r > 5$ kpc and the solid orange line for $r > 0.5$ kpc. At high resolution, the dips in

![Figure 3](https://example.com/figure3.png)
confirmed CO detection lie between 7–12 with a distribution peaking at 10–12 (see Figure 11, Prasad et al. 2018). Making more definitive comparisons with observations will require deprojection of mock observations of simulated clusters, so that the values of \( \text{min}(t_{\text{cool}}/t_{\text{ff}}) \) derived from the simulations can more accurately reflect what observers actually measure. However, such an analysis is beyond the scope of this short paper.

5 DISCUSSION

We find that many of the unique features of the Phoenix cluster core are consistent with a numerical simulation of kinetic AGN feedback fueled by cold gas accretion. They do not necessarily signal a different evolutionary pattern for Phoenix, but rather motivate higher sensitivity observations of the most centrally peaked systems to assess how compatible the observed distribution of \( \text{min}(t_{\text{cool}}/t_{\text{ff}}) \) is with the simulations.

Phoenix has a high current SFR but its fraction of young stars indicates that it has not been forming stars at that rate for very long. The observed amount of molecular gas (\( M_{\text{cold}} > 10^{10} \, M_{\odot} \)) most likely has originated in gas cooling from the surrounding hot atmosphere over 50–120 Myr (Russell et al. 2017). Pure cooling for a few hundred Myr (Figure 4) is enough to make the cluster look like a pure cooling flow, consistent with our interpretation of a short cooling cycle. Moreover, pure cooling in Phoenix for ~1 Gyr would create a cold gas reservoir of \( 10^{12} \, M_{\odot} \), more than an order of magnitude larger than what is observed (Russell et al. 2017).

We cannot rule out that Phoenix has a black hole with an unusually low mass for its halo mass and therefore cannot produce enough kinetic feedback, as suggested by McDonald et al. (2019a). However, if the black hole is indeed ineffectual, the feedback failure must be a very recent phenomenon otherwise, for the reasons noted above, we would expect a higher fraction of young stars and a much higher reservoir of cold gas than observed. McDonald et al. 2012 used the scaling relations between spheroid stellar mass and central black hole mass (Bennert et al. 2011) to estimate a mass ~ \( 1.8 \times 10^{10} \, M_{\odot} \) for the SMBH, which would make it one of the most massive in the universe. Owing to its large Eddington accretion rate, such a massive SMBH can provide sufficient kinetic feedback through accretion at \( 10^{-5} \) times the Eddington rate. The cavity power inferred in Phoenix may therefore be an underestimate, given our hypothesis that the AGN is in the initial stages of an outburst and may still be rapidly inflating its cavities.

6 CONCLUSIONS

The principal conclusions of this work are as follows:

- Surface brightness snapshots of our cluster simulations, along with the corresponding radial profiles of density, entropy, temperature, and \( t_{\text{cool}}/t_{\text{ff}} \) during transitions from a cooling phase to an AGN outburst, are similar to observations of Phoenix (although the halo mass of the simulated cluster is a factor of few smaller).
Phoenix is not necessarily fundamentally different from other cool-core clusters. We may have caught it at the end of a cooling state, just as AGN feedback is turning back on. The thermodynamic and various timescale profiles from our simulation is in very good agreement with Phoenix profiles once the profiles are scaled to account for mass and redshift differences.

Phoenix does not necessarily signal the failure of kinetic SMBH feedback. Similar phases may also be seen in lower mass halos. However, the cooling phases in simulated systems are more frequent in more massive halos, given a fixed efficiency parameter.

Deeper observations with a higher photon count within $r < 10$ kpc of centrally peaked galaxy clusters may be required to measure $\min(\frac{t_{\text{cool}}}{t_{\text{ff}}})$ accurately, since $\frac{t_{\text{cool}}}{t_{\text{ff}}}$ during a cooling phase is close to the minimum value only over a small range in radius ($r \ll 10$ kpc).

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