Feedback stimulated by uplift in Galaxies

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Outline:
- the $t_c/t_{ff}$ thermal instability indicator: does it work in modern galaxies?
- cooling time/entropy threshold – molecular gas
- cold & hot gas flows important element of feedback
- *Stimulated Feedback*, uplift & circulating gas flows

Cambridge, December, 2016
Cooling in central galaxies is apparently stabilized by AGN feedback
How is feedback, star formation fueled?

Perseus
Fabian + 00, 2008
Central Galaxies + short cooling times = molecular gas

- central cooling times < 1 Gyr
- single dish observations: molecular gas > $10^9 M_\odot$
- Forming stars at tens to hundreds of solar masses per yr
- molecular gas cooling from X-ray atmosphere (Edge 01, Salome & Combes 03)

Exciting ALMA results to follow in Helen Russell’s talk
ALMA: molecular gas flows, unsettled gas distribution

Phoenix

\[ M_{\text{H}_2} = 2.7 \times 10^{10} \, M_\odot \]

Russell + 16

Abell 1835

\[ M_{\text{H}_2} = 5 \times 10^{10} \, M_\odot \]

McNamara + 14

PKS 0745-191

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Russell + 16
Renewed interest in thermal instability inspired by several influential papers:

Cowie, Fabian Nulsen 80
Nulsen 86
Pizzolato & Soker 06

*McCourt + 2012 – revival paper*
Sharma + 2012
Li & Bryan 2014
Li+2015
Gaspari + 2011,12, 16
Voit + 2015
Voit & Donahue 2015
Prasad + 2015
Voit + 2016

What role, cooling time, free-fall time, entropy?

\[ \frac{t_c}{t_{ff}} < 10 \quad \frac{t_c}{t_{ff}} < 1 \]

gravity
**Gravity matters:** Feedback scales with halo mass & *central cooling time* over two decades in mass, four decades in jet power.

Scaling is consistent with M-σ relation (Ferrarese & Merritt 00): $M \sim \sigma^5$
assuming $P_{jet} \sim L_{cool} \sim M^{1.75}$, *assuming jet power governed by feedback*

Trend vanishes in halos with central cooling times $\geq 1$ Gyr

Why? -- *cooling time/entropy instability threshold—Cold Accretion*
Sharp threshold for onset of star formation (thermal instability)

Star formation

Nebular emission

Cool gas & Star formation linked to cooling, X-ray atmospheres
Gravity & cooling: key to thermally unstable cooling

*free-fall speed:*

dynamical timescale: $t_{\text{dyn}} = (2r/g)^{1/2}$

*terminal speed:*

buoyancy timescale: $t_B \sim r(2mg/\rho AC_d)^{-1/2}$

Significant new results:

Precipitation Model:

$t_c/t_{ff} \approx (\delta \rho/\rho)^{-1} \leq 10$ onset of non-linear cooling instabilities

*a.k.a. “precipitation” ...*  
McCourt +12, Sharma + 12, Voit + 15, Li + 15

This idea can be tested  
Hogan + 16
Is $t_c/t_{ff}$ a better probe of molecular gas than $t_c$ alone? Apparently not --- free fall time adds noise.

Low $t_c/t_{ff}$ driven primarily by cooling time, not free-fall time. To do properly, *must* deproject and measure acceleration carefully. $t_c/t_{ff}$ rarely falls below 10 -- difficult for precipitation models -- indicates stable atmospheres!

Hogan + in prep
Cooling time dominates the ratio
Molecular Gas likely cooled from Hot Atmosphere
data from Edge 01, ...

- Cold & hot mass correlated; easily supplied by hot phase
- Molecular gas $>10^9 \text{ M}_\odot$ occurs suddenly when $t_c < 10^9 \text{ yr}$
- Radio power uncorrelated with total molecular gas mass
Simulations: swings in atmospheric density, jet power, molecular gas, correlate with $t_c/t_{ff}$.

Key simulations: **Uplift – Li & Bryan 14**


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- large swings in gas density, cooling time, $t_c/t_{ff}$ *not observed*
- uplift *is observed*
-- Central Cluster Galaxies Rich in Molecular Gas: $> 10^9 \, M_\odot$

-- No trend with jet power in total gas mass, but plenty of fuel
Radio Mode Feedback is Gentle: not large central density swings

- Density swings only factors of several
- Precipitation models predict 2 decades of variation - not observed

\[ \approx 5 \times \delta n_e \text{ at } 10 \text{kpc} \]
less at 1 kpc much unrelated to AGN

\[ 10^{46} \text{ erg s}^{-1} \]

\[ 10^{43} \text{ erg s}^{-1} \]

rock-steady despite >4 dex energy injection

no trend between \( t_c / t_{ff} \) and molecular gas mass or star formation rate
we know only that when \( t_c < 10^9 \text{ yr} \), stuff happens... feedback is subtle
Entropy profiles of cool core clusters are power laws

- Voit, Kay, Bryan profile beyond ~50 kpc
- Consistent with Panagoulia, Fabian, Sanders < 50 kpc
Conjecture: “stimulated feedback”

McN + 16

Assumptions:

1) Cooling time threshold is the key observation to be understood

2) $t_c/t_{ff} \leq 1$ classical criterion for thermal instability to be satisfied
   
   infall time, not free-fall time, may satisfy criterion

   to achieve 2, low entropy gas must be lifted to higher altitude – stimulated feedback

ALMA + Chandra surprises:

Uplift (circulation) in essentially all gas phases, molecules to plasma
slow gas (infall) velocities indicate terminal speed governs thermal instability

McN+16, 14, Russell+16, Kirkpatrick + 15
Simionescu +08, ... others

see Li & Bryan 14: uplift important in feedback simulation
Stimulated Feedback: \( t_c/t_f < 1 \) requires AGN to lift gas

McN + 16

no nebulae no bubbles
e nebular emission/bubbles
e nebular emission/bubbles

cooling time

\[ t_c/t_f \leq 1 \]

free-fall time

\[ t_c/t_f \]

the spoiler

A2029 M87 MS0735

S*Simulated Feedback:

\[ t_c/t_f \leq 1 \] requires AGN to li2 gas
Uplifted Hot Gas

$R_{Fe} \sim 300$ kpc

Powerful thrust:

$P_{jet} \sim 3 \times 10^{46}$ erg s$^{-1}$

$E_{jet} \sim 10^{62}$ erg

Lifted/displaced mass $\sim 10^{10}$ M$_{\odot}$ $\sim 100$ M$_{\odot}$ yr$^{-1}$

See also Simionescu + 08, Kirkpatrick 09,11,14, Gitti + 11
Hot outflow mass comparable to molecular gas mass

- Outflow rates several to a few hundred solar masses per year
- A few to a few tens of % of the cooling gas is re-circulated
- Outflow mass consistent with molecular gas masses

Kirkpatrick & McNamara 15
ALMA: uplifted molecular gas and hot gas cooling, circulating

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Summary

**Uplift** ubiquitous, important

Precipitation models, $t_c/t_{ff} < 10$ inconsistent with observation

$t_c/t_{ff} < 1$ achieved by lifting low entropy gas to higher altitudes

*stimulated feedback*

Low molecular cloud velocities observed in many systems

pinned to hot gas? (c.f., Hitomi Perseus result)

**TI criterion:** $t_c/t_l \leq 1$,

infall time bounded by free-fall and terminal speeds

Stimulated feedback conjecture – must be tested

*must recover cooling time thresholds*