Models of AGN Feedback

Perseus cooling flow

Simulated X-rays

Li & Bryan 2014

Mrk 231
X-ray cavities

Inefficient star formation
Behroozi et al 2013

Cool-cores in 70-90% clusters
(Edge et al 1992)

Radio jets

The others are mergers, un-relaxed

MS0735.6+7421 cluster
(McNamara et al. 2009)
Outline

1- AGN feedback moderating cooling flows

2- SN+AGN inflow/outflow in galaxies

3- Mechanisms -- Energetics

4- Modes of quenching

\[ \begin{align*}
M_{BH} &= 1 - 2 \times 10^{-3} M_{gal} \\
E_{BH} &\sim 0.1 M_{BH} c^2 \rightarrow \frac{E_{BH}}{E_{gal}} > 80 \\
E_{gal} &\sim M_{gal} \sigma^2
\end{align*} \]

Gaibler et al 2012
Two main modes for AGN feedback

Quasar mode: radiative or winds
When luminosity close to Eddington, young QSO, high z
\[ L_{\text{Edd}} = 4\pi G M_{\text{BH}} m_p c / \sigma_T \Rightarrow M_{\text{BH}} \sim f \sigma^4, \ f \text{ gas fraction} \]

Same consideration with radiation pressure on dust, with \( \sigma_d \)
\[ \sigma_d / \sigma_T \sim 1000, \ \text{limitation of } M_{\text{bulge}} \text{ to } 1000 \ M_{\text{BH}} ? \]

Radio mode, or kinetic mode, jets
When \( L < 0.01 L_{\text{edd}} \), low z, Massive galaxies, Radio E-gal
Not destructive: keeps a balance cooling-heating
Radiatively inefficient flow ADAF

High frequency of cooling flows in clusters,
Low-luminosity AGN Seyferts..
1- Gas flow in cool core clusters

Star formation (green)
Canning et al 2014

Molecular Gas
Salomé et al 2006

X-ray Perseus A, Fabian et al 2003
Cold gas in filaments

Inflow and outflow coexist

The molecular gas coming from previous cooling is dragged out by the AGN feedback

The bubbles create inhomogeneities and further cooling

The cooled gas fuels the AGN

Velocity much lower than free-fall

Salome et al 2008
Numerical simulations (Revaz, Combes, Salome 2007)

Buoyant bubbles, compression and cooling at the surfaces
+Cold gas dragged upwards
Large variety of simulations

Cooling rate ~ boosted Bondi rate, but Cold gas accretion better
Radiation pressure insufficient

Mechanical feedback with jets or winds

Success in moderating the cooling, keeping the CC structure

Efficiency scaled to the structure scale
Gaspari et al 2012
3e-4 (E-gal) 5e-3 (clus)
Comparison between models

During a merger, accreted gas fuels SFR and BHAR
BHAR delay, since SN-feedback too strong at the beginning (Wild et al 2010)

**Comparison:**

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**Models:**

- Bondi accretion
- Other accretion models

**Graph:**

- Wild et al.
- SDH
- BS
- WT
- HPMK
- Chen et al.

**Legend:**

- SDH Springel+05
- BS Booth+09
- WT Wurster+13
- HPMK Hobbs+12

**Thacker et al 2014**

**Diagram:**

- Wild et al.
- DQM
- ONB
- PNK0505
- Chen et al.

**Legend:**

- DQM Debuhr +11
- ONB Okamoto+08
- PNK Power+1
2- Molecular outflows

Mrk 231
AGN and also nuclear Starburst, $10^7$-$10^8$Mo
Outflow $700$Mo/yr

IRAM Ferruglio et al 2010

On kpc scales, $\rightarrow$ Maiolino et al 2012
affects the galaxy, quenches SF

Blue wing

Red wing

Cicone et al 2012

$dM/dt = 3v \frac{M_{OF}}{R_{OF}} \sim 1000$ Mo/yr, (5xSFR)
Kinetic power $\sim 2 \times 10^{44}$ erg/s $\rightarrow$ AGN

High density, HCN, HCO+, Aalto et al 2012
Relations outflows with AGN

For AGN-hosts, the outflow rate correlates with the AGN power.

\[ \frac{dM}{dt} \propto 20 \frac{L_{\text{AGN}}}{c} \]

Can be explained by energy-driven outflows (Zubovas & King 2012)
3-Why molecular outflows?

Outflowing gas is accelerated by a shock, and heated to $10^6$-$10^7$K 

Molecules should be dissociated at such temperatures
Even if cold clumps are carried out in the flow ➞ shock signature?

Radiative cooling is quick enough to reform molecules in a large fraction of the outflowing material (Zubovas & King 2014)

With $V \sim 1000$km/s, and $dM/dt \sim 1000$ Mo/yr, efficient cooling produces multi-phase media, with triggered star formation
AGN winds more than SF outflows?

Zubovas & King 2014

Cooling efficient (free-free, metals)
Flow unstable, if \( R = \frac{P_{\text{rad}}}{P_{\text{gas}}} < 0.5 \) (Krolik 1981), and
\[ R \sim 0.07 \frac{M_{\text{BH}}}{M_{\text{crit}}} f_{\text{EDD}} \sim 0.07 \]
\( \Rightarrow \) Multiphase, with RT instabilities

Time-scale for cooling \( << 1 \text{Myr} \)
At kpc scales, \( \Rightarrow \) SF induced

The SF results in a Luminosity
Comparable to \( L_{\text{AGN}} \sim 100\text{Mo/yr}! \)

This means that SB or AGN outflows are difficult to disentangle
All could be due to AGN
Energy-conserving outflows?

If the cooling is very efficient, $\rightarrow$ momentum-conserving outflow

But for very fast winds $> 10,000 \text{km/s}$, radiative losses are slow
$\rightarrow$ energy-conserving flow (Faucher-Giguère & Quataert 2012)

In some cases, even slow winds $v_{\text{in}} \sim 1000 \text{km/s}$ driven by radiation pressure on dust, could be energy-conserving
 Push by the hot post-shock gas, boost the momentum $V_s$ of the swept-up material

Boost of $v_{\text{in}}/2 V_s \sim 50!$ Explains why momentum flux $>> L_{\text{AGN}}/c$

// Adiabatic phase, or Sedov-Taylor phase in SN remnant
Slow cooling -- High momentum fluxes

$T_{\text{behind } R_{\text{SW}}}$

Full: protons  
Dash: electrons  
$T_{\text{Comp}} = 2 \times 10^7 \text{K}$

Costa, Sijacki, Haehnelt, 2014
Outflow solutions

Represent the typical case of Mrk231, face-on, R~3kpc V~1000km/s

Momentum flux = 15 $L_{\text{AGN}}/c$

$\dot{M}_s v_s^2 \approx \frac{1}{2} \dot{M}_\text{in} v_{\text{in}}^2$
Winds launch

From accretion disks, as seen in UV abs lines
BAL quasars, or from X-rays coronae
Thermal heating (Compton) makes the gas reach Vesc
Radiation on electrons (> Eddington)
Or even radiation pressure on dust

Or magnetic driving
(Proga 2003, 2005)
More realistically,
all driving mechanisms together!
Quasar mode: Two-phase simulations

Most of the outflow kinetic energy escapes through the voids
Positive and negative feedback
Cold gas is pushed by ram-pressure
More feedback on low-density gas

Could lead to $M-\sigma$ relation

Nayakshin 2014
Radio mode: Fractal structure 2pc-1kpc

Efficient relativistic jets; Influence of the porosity
*Wagner & Bicknell 2011*
Positive AGN feedback  
Radio jets triggered SF  

Silk 2005, Dubois et al 2013  

Young, restarted radio loud AGN 4C12.50  
The outflow is located 100 pc from the nucleus  
where the radio jet interacts with the ISM  

Morganti et al 2013, Dasyra & Combes 2012
Feedback in low-luminosity AGN

NGC 1433: barred spiral, **CO(3-2) with ALMA**
Molecular gas fueling the AGN, + outflow // the minor axis

\[
M_{\text{H}_2} = 5.2 \times 10^7 \, M_\odot \text{ in FOV}=18''
\]

100km/s flow
7% of the mass= \(3.6 \times 10^6 \, M_\odot\)
Smallest flow detected

\[
L_{\text{kin}} = 0.5 \, \frac{dM}{dt} \, v^2 \approx 2.3 \times 10^{40} \, \text{erg/s}
\]
\[
L_{\text{bol}} (\text{AGN}) = 1.3 \times 10^{43} \, \text{erg/s}
\]
Flow momentum > \(10 \, L_{\text{AGN}}/c\)

*Combes et al 2013*
4- Modes of Quenching

- **Rapid:** Feedback from SF, from AGN
- **Slow:** Morphological quenching, after bulge formation

T-quench $\sim$2-4 Gyr

Schawinski 2013
Feedback loop?

Torque limited growth

 Mostly gas accretion, sometimes Mergers (but not essential)

 Numerical evolution
 M-σ relations for seeds

 Effects of initial conditions are Quickly erased

 $dM_{\text{BH}}/dt \sim \text{SFR with scatter}$
 No feedback loop required

Angles-Alcazar et al 2013
AGN feedback in mergers

SFR $\sim \rho^n$ with $n=1, 1.5, 2$
SN feedback +
BH growth and associated feedback

Sub-grid physics
How much feedback?

Springel et al. (2003-2005), Hopkins et al. 2006

Gabor & Bournaud 2014:
No quenching effect
Several modes simulated

**Quasar mode**, when \( \frac{dM_{\text{BH}}}{dt} > 0.01 \text{ Edd} \) – Energy released spherically

**Radio-jets** otherwise: \( V = 10^4 \text{ km/s} \), in a cylinder perp. to the disk

Efficiency to form stars reduced by a factor 7

Decrease the baryon concentration

*Dubois et al 2012, 2013*

Energy-driven, much more efficient than momentum-driven

**AGN outflows** with \( > 10 \text{ Ledd/c} \)

Entrained cold gas \( > 10^9 \text{ Mo} \)

If after-shock cooling with metals

*Costa et al 2014*
SUMMARY: AGN feedback

- AGN feedback is very efficient in Cool Core clusters to moderate the cooling: mechanical with radio jets, cold gas accretion

- Molecular outflows are now observed frequently, around AGN, $v=200-1200\text{ km/s}$, $10^7-10^9\text{ Mo}$, load factors $>3$

- Mechanisms: Quasar modes (winds), Radio modes (jets), for more massive galaxies with lower Edd ratios (and lower $z$)
  Either mass accretion or mergers

- Energy-conserving flow: Momentum boost $20 L_{\text{AGN}}/c$