AGN negative and positive feedback

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Negative feedback extreme case: quenching of star formation

AGN negative feedback invoked to:
- Transform star forming into passive at high masses
- Reproduce the mass function at high masses
- Account for the BH-galaxy scaling relations

Star forming galaxies, gas rich, young (blue) stellar population

Stellar Mass Function

DM halos

AGN-driven quenching?

Passive, quiescent, little/no gas, older (red) stellar population

Henden+18
Star formation quenching: causes and mechanisms

**Cause** → **Environment** → **Starburst** → **AGN** → **Mass**

- **Environment**
  - Gas removal (ejective)
    - Ram-pressure stripping

- **Starburst**
  - SF Efficiency Suppression
    - “strangulation”
  - Starvation
    - Wind halo heating
  - ISM heating and turbulence

- **AGN**
  - AGN winds
  - Jet/wind halo heating
  - Gravitational shock heating

- **Mass**
  - Q>1
    - ‘morphological’ (gravitational stability)

Identifying the primary cause often difficult because of degeneracies
AGN ‘ejective’ mode

Blast wave: energy-driven wind

- Massive outflow
- Wind Kinetic Power ~ a few % $L_{\text{AGN}}$
- Momentum rate ~ $20 \times L_{\text{AGN}}/c$

(modulo wind-ISM coupling factor)

Radiation pressure on dusty clouds

- Wind Kinetic Power < 1 % $L_{\text{AGN}}$
- Momentum rate ~ $1-5 \times L_{\text{AGN}}/c$

- Instability problem

References:
- King+10
- Zubovas+12
- King & Pounds 2015
- Harrison+18
- ...
3D simulations:
AGN-driven outflows eject gas from central regions, but primarily escape through low density, least resistance regions.

Certainly major negative feedback but probably not quenching star formation across entire galaxy.
**Theory/simulations: halogen heating**

- Radio-jets
- AGN-driven Winds
- ‘preventive’ feedback
- delayed quenching
- maintenance mode

**Halo heating**

**Buoyant hot bubbles**

- Sijaki+07
- Weinberger+17
- Bourne+17
- Gaspari+17
- (many other)

- Pillepich+17
- Weinberger+17
- Bowens+17
- Costa+18
Observations: is AGN ‘ejective’ mode effective?

Outflow rate > SFR

⇒ AGN-driven outflow can have a major negative feedback
Yet, AGN-driven outflows may be not capable of quenching?

Broad dispersion:
- either Energy-driven with broad range of coupling
- or radiation pressure driven

Kinetic power
- cold gas outflows (local)
- cold gas outflows (high-z)
- ionized gas outflows

Momentum rate

Cicone+14, Fiore+17, Fluetsch+18, Bischetti+18, Tombesi+15, Feruglio+17, Veilleux+17...
Directly mapping negative feedback effect outflows at high-z

Outflows in the most powerful quasars at z~1-2

Carniani et al. 2016
Cano Diaz et al. 2012
Cresci et al. 2015

Half full glass: Clear evidence that star formation is suppressed in regions affected by the quasar-driven outflow

Half empty glass: The quasar driven outflow escapes without quenching star formation over the entire galaxy
Statistical evidence for suppressed Star Formation in AGN hosts?

Conflicting claims:

- Suh+17, Mullaney+13, Santini+13, Rosario+15, Del Moro+15, Ellison+16, Brusa+09: AGN hosts on and above the Main Sequence

- Mullaney+12, Matsuoka+15, Bongiorno+12, Brusa+09, Georgakakis+14, Ellison+16: AGN hosts on and below the Main Sequence
Correlations between AGN luminosity activity and SFR... not really what expected from negative feedback... different timescales?

- Netzer+07,09
- Harrison+16
- Bernhard+16

Correlation only at high luminosities

- Del Vecchio+15
- Lutz+10
- Shu+10
- Rosario+13

Stack in X-ray -> better technique to deal with AGN flickering
No correlation between outflow and SFR (opposite trend). Either no feedback from outflows or delayed effect

Woo+17, Balmaverde+15, Leung+17
Directly looking at the effect of gas removal:
Gas content in AGN host galaxies
-> conflicting results

Rosario+18
Maiolino+97: No difference

Vito+14: Gas rich

Fiore+17, Kaddad+17, Brusa+16, Perna+18: Gas Poor
Obscured Quasars (Kaddad+17, Brusa+16,+17, Perna+18)

- Low gas fraction (→ negative feedback?)
- High star formation efficiency

Quasars live in a different population of galaxies?
Fraction of outflowing gas that escapes the galaxy

Vast majority of outflowing gas rains back onto the galaxy

-> ejective feedback effective only in the central region?
AGN-induced ISM turbulence/heating
-> suppression of star formation efficiency

OK... but can only be temporary... it’s a “time bomb”!

Alatalo+15, Costa+18
Halo heating
-> prevents cooling onto the galaxy
- ‘preventive’ feedback
- delayed quenching
- maintenance mode

Heating ~ Cooling

Power in (bubbles)

Power out (X-rays)
Hot bubbles also capable of lifting large amount of cold gas from the host galaxy (=> quenching role)
Halo heating through quasar-driven winds: difficult to test presence of hot gas

Attempts to detect associated S-Z by using CMB data and stacking at quasar positions (Planck, ACT)

ALMA needed to make progress

Ruan+15
Verdier+16
Crichton+16
Soergel+17
tentative (marginal) detection ~ in agreement with models
Negative feedback summary

- Ejective mode:
  important regulatory mechanism (central regions)
  probably no quenching

- Suppression of star formation efficiency
  (ISM turbulence/heating): may be, but temporarily?

- Jet/wind halo heating:
  effective (delayed/preventive)
  but yet to be fully tested
AGN positive feedback

Two modes:

- SF triggered in host galaxy or CGM by AGN-driven jet/outflow

- SF taking place *inside* the outflowing gas
AGN positive feedback

Two modes:

- SF triggered in host galaxy or CGM by AGN-driven jet/outflow

Geibler+12
Silk+13
Mukherjee+18
Many others...
Examples of jet/outflow induced star formation

But
SFR $\sim 0.5\text{--}0.1 \, M_\odot/\text{yr}$

Sanatoro+16

Crockett+12
Croft+06
Cresci+15
Star formation triggered by quasar-driven winds at high-z

Quasar @ z=1.59
SINFONI IFU spectrum

[Narrow H\textalpha\xrightarrow{\rightarrow}\text{Star Formation}]

low velocity [O\text{III}]

high velocity [O\text{III}]

[O\text{III}] 5007

positive feedback

negative feedback

SFR \sim 230 \, M_\odot/yr!

Cresci+15
AGN positive feedback

Two modes:

- SF triggered in host galaxy or CGM by AGN-driven jet/outflow

- SF taking place *inside* the outflowing gas
Several models do expect star formation *inside* outflows

→ Stars should form at high velocities on ~radial orbits

⇒ major potential implications!

  e.g. Contribution to the galaxy spheroidal component...

**Expected also by properties of outflowing gas:** molecular dense, cold and clumpy gas...

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Zubovas+13,17, Zubovas & King ’13
Silk+15, +17
Ishibashi & Fabian +14, +15,+17 Nayakshin+12,
Zachary+14, Gaibler+12, Wang & Loeb ’18
Dugan+2014, El-Badry+2016,
Mukherjee et al. 2018
A large fraction of the outflowing molecular gas is
- very dense $\sim 10^5$-$10^6$ cm$^{-3}$
- very clumpy (clump sizes 1-100 pc)

Gas properties similar to star forming regions

Lin+16
Aalto+15, 16
Walter+17
Alatalo+15
Gonzalez-Alfonso+17
Zschaechner+15
Tunnard+15
Sakamoto+08

Mrk231
HCN (dense gas tracer)

High velocity dense gas

Finn+15
Borguet+12
Feruglio+15
Pereira-Santaella+16

Pereira-Santaella+16
Aalto+15
Finn+15
Borguet+12
Feruglio+15
Manga Survey: Median BPT classification of galactic outflows

~30% of galactic outflows classified as “star forming”
-> star formation inside the outflow (confirmed by near-IR diagnostics for some of them)

Extrapolation to high-z implies important contribution to galaxy formation

Gallagher+18
Maiolino+15
Implications of star formation inside outflows

Contribution to the formation of spheroidal component of galaxies (bulges, halos, ellipticals)

- radial velocity of stars formed in outflow

BH-spheroid correlations

Supernovae outside galaxies
  -> \textit{In-situ} chemical enrichment
  -> \textit{In-situ} halo heating

- Re-ionization of the Universe

- escaping stars:
  - intra-cluster light
  - NIR background

Bulge-Halo stars
Elliptical gal. stars

Zubovas & King '13
Ishibashi & Fabian '17
Mukherjee+18
Wang & Loeb '18
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\begin{equation*}
L(\text{AGN}) \sim v^{4.5}
\end{equation*}

\text{Fiore+17}

Automatically gives the observed $M_{\text{BH}}-\sigma_\star^{4-5}$ relation
Positive feedback summary

- **Induced star formation in the galaxy:**
  - several clear cases
  - locally modest effect,
    - possibly much stronger at high-z

- **Star formation inside outflows:**
  - now detected in multiple cases
  - potential major implication:
    - formation of spheroids
    - BH-spheroid relations
Thank you!
Spare slides
Just to make things even more puzzling...

**Hard X-ray selected AGNs:**
in green valley... but centrally Star Forming

\[ \text{SFR} \left[ M_\odot \text{ yr}^{-1} \right] \]

\[ 10^{-2} \quad 10^{-1} \quad 10^{0} \quad 10^{1} \quad 10^{2} \]

\[ 10^{9} \quad 10^{10} \quad 10^{11} \]

\[ \text{HRS} \quad \text{BAT Sy1} \quad \text{BAT Sy2} \quad \text{BAT LINER} \]

\[ -> \text{further evidence for a delayed (indirect) effect?} \]

Shimizu+15, Mushotzky+14
Hitomi spectrum: surprisingly low turbulence

Mechanical Halo heating, propagated $4\pi$ through sound waves

$\sigma = 160 \text{ km/s}$

Sanders+15, McManera+17
First observational evidence of star formation inside an AGN-driven outflow

IRAS 2312-59
Maiolino+17

- SFR in outflow ~15-30 M☉/yr
- Most stars formed in the outflow are bound -> bulge/halo
Star formation boosted in shocked gas

Multiple cases in our Galaxy and in other galaxies

Zavagno et al. 2010
Lim et al. 2018
Baug et al. 2018
Dwarkadas et al. 2017
Duronea et al. 2017
Figueira et al. 2017
Deharveng et al. 2015
Ladeyschikov et al. 2015

Stars formed in the shocked front

Crockett+12
Santoro+17
Croft+06
Seyfert galaxy NGC5643

But triggered SFR $\sim 0.03 \, \text{M}_\odot$/yr

Cresci+15