Observational evidences of AGN feedback

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AGN11, Trieste September, 23 2014
Outline

1- Observational evidences of AGN feedback in action (not outflows!), near and far, review recent results

2- How they compare with model predictions

3- Open questions

4- What is needed to progress
Three key questions
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Why did galaxies during their evolution stop to form stars?
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- Why black holes in galactic nuclei have masses proportional to spheroid masses?
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What are the mechanisms leading the transition from gas rich, star-forming, galaxies, to passive spheroids, deprived of most of their gas?

Why black holes in galactic nuclei have masses proportional to spheroid masses?

One of the main candidates for driving these transformations are powerful winds and shocks launched from accreting black holes in active galaxy nuclei (i.e. feedback)
SMBH and stellar growth correlated

The BH mass density obtained integrating the AGN L.-F. and the CXB ~ that obtained from local bulges

How are they created: need to understand BH growth and feedback

tight correlation between $M_{\text{BH}}$ and bulge properties (e.g. Richstone+ 1998)
Massive galaxy density and colors: AGN feedback required

Menci+ 2006  Croton+2006
Massive galaxy density and colors: AGN feedback required

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Without AGN heating SAMs:
Massive galaxy density and colors: AGN feedback required

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1. overpredict luminosities of massive galaxies by ~2 mags
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Massive galaxy density and colors: AGN feedback required

Without AGN heating SAMs:
1. overpredict luminosities of massive galaxies by ~2 mags and/or
2. predict a number of massive blue galaxies higher than observed
Scaling relations

Star-forming galaxy *main sequence*: a nearly linear relationship between stellar mass and SFR, flattening at the highest stellar masses and evolving with the redshift.
Scaling relations

\[
\log \left( \frac{t_{\text{dep}}}{f_1(z)} \right) = -0.46 (0.016) \times \log(\text{sSFR}/\text{sSFR}(\text{ms}))
\]

\[
\log \left( \frac{t_{\text{dep}}}{f_1(z) \times g_1(\text{sSFR}/\text{sSFR}(\text{ms}))} \right) = -0.002 (0.026) \times (\log(M_*) - 10.5)
\]
Scaling relations

Genzel+2014

\[ \text{sSFR} = \frac{\text{SFR}}{M_{\text{star}}}; \quad t_{\text{depl}} = \frac{M_{\text{gas}}}{\text{SFR}} \]
Scaling relations

Gas fraction $= \frac{M_{\text{gas}}}{M_{\text{star}}}$

AGN feedback may be the driver for the decrease of the gas fraction and for the quenching of SFG at $\log M_{\text{star}} > 1.8$
Scaling relations

\[ \log\left(\frac{M_{\text{molgas}}}{M_{\star}}/f_2(z)/g_2(sSFR/sSFR(\text{ms},z))\right) = -0.35 (0.030) \times (\log(M_{\star},10.77)) \]

Gas fraction = $\frac{M_{\text{gas}}}{M_{\star}}$

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AGN Feedback & accretion mode
**AGN Feedback & accretion mode**

### Quasar mode
- Major mergers
- Minor mergers
- Galaxy encounters
- **Activity periods are strong, short and recurrent**

**AGN density decrease at z<2 is due to:**
- Decrease with time of galaxy merging rate
- Decrease with time of encounters rate
- Decrease with time of galactic cold gas left available for accretion

Feedback is driven by AGN radiation

AGN Feedback & accretion mode

Quasar mode
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Radio mode
- Low accretion-rate systems tend to be radiatively inefficient and jet-dominated
- Feedback from low luminosity AGN dominated by kinetic energy
- Low level activity can be ~continuous
  Croton+ 2006

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- Decrease with time of galaxy merging rate
- Decrease with time of encounters rate
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Feedback is driven by AGN radiation
Somerville+2003
AGN winds and outflows are ubiquitous

- radio jets (relativistic)
- ultra fast outflows (UFO, moderately relativistic)
- ionized gas outflows (BAL, NAL, [OIII], [CII] $v \sim 1000-30000$ km/s, massive)
- atomic gas outflows (absorption NaI, HI, $v \sim 100-1000$ km/s)
- molecular outflows
  (OH, CO, HCN, $v \sim 200-2000$ km/s, MASSIVE
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  Sturm+2011,
  Spoon+2008,2011)
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Mrk231 HCN,HCO+$^*$

Aalto+2012

Rupke & Veilleux 2011, 2013

North

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Bad news: Feedback observations are difficult

Radio-mode (jet driven) strong evidence of feedback, observed frequently

But quasar-mode feedback observations are still rare, both in single objects and statistical samples.
Radio-mode feedback
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Power to excavate cavities proportional to X-ray luminosity
Radio-mode feedback

Power to excavate cavities proportional to X-ray luminosity

Power in cavities proportional to AGN radio luminosity
**Radio-mode feedback**

Power to excavate cavities proportional to X-ray luminosity

Power in cavities proportional to AGN radio luminosity

Only BCG in clusters with *low inner entropy* (short cooling time) have an active nucleus: **cold accretion!**
Power to excavate cavities proportional to X-ray luminosity

Power in cavities proportional to AGN radio luminosity

Only BCG in clusters with low inner entropy (short cooling time) have an active nucleus: cold accretion!

..and only BCG with low inner entropy are actively forming stars!
**Quasar-mode: ionized phase outflows**

AGN feedback via nuclear extended (2-3 kpc) outflows widespread among massive z~2 SFG of the main sequence.

Mass outflow rates \(\sim 100 \text{ Msun/yr}\)

**Spatial offset between broad/narrow Halpha => feedback**

Genzel+2008 Forster Schreiber +2014
Genzel+2014

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Quasar-mode: ionized phase outflows

Cano-Diaz+2012

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Quasar-mode: ionized phase outflows

Cano-Diaz+2012

\[ M_{\text{out}}^{\text{ion}} = 5.33 \times 10^7 \frac{C L_{44}(\text{[OIII]})}{\langle n_e^3 \rangle 10^{[\text{O/H}]} } M_\odot \]

\[ \dot{M}_{\text{out}}^{\text{ion}} = \langle \rho \rangle v v \Omega R^2 \]

\[ \dot{M}_{\text{out}}^{\text{ion}} = 164 \frac{C L_{44}(\text{[OIII]}) v_3}{\langle n_e^3 \rangle 10^{[\text{O/H}]} R_{kpc} } M_\odot \text{ yr}^{-1} \]

\[ v_{\text{out}} \sim 1000-10000 \text{ km/s} \]

\[ \log L(\text{[OIII]} ) = 42-44 \text{ ergs/s} \]

\[ \log n_H = 3-4 \quad NELR \]

\[ r \sim 1-10 \text{kpc} \]

\[ M_{\text{out}} \sim 10-1000 M_\odot \text{/yr} \]
**Quasar-mode: ionized phase outflows**

Brusa+2014, Cresci+2014  

**NEXT TALK**

**XID 2028**

- log$L_x$~45
- log$L_{bol}$~46
- SFR~450 $M_{\odot}$/yr
- log$M_{\ast}$=11.7
- $M_{out}$~1000 $M_{\odot}$/yr

Spatial anticorrelation  
fast/quiescent gas

**Halpah map**

**[OIII] broad**
Mrk231

- nearest QSO (z=0.042)
- most luminous ULIRG in the local Universe $L_{IR}=3.6 \times 10^{12} L_\odot$
- >40% $L_{bol}$ in SB activity
- late-state merger
- X-ray under-luminous AGN: $L_x=10^{43}$ erg/s
- BAL QSOs
- Expanding shells on Kpc scales

**Dust enshrouded AGN/star-forming galaxy**
Outflows observed in the ionized, neutral and molecular gas

\[ \dot{M}_{\text{out}} [700 \, \text{M}_\odot/\text{yr}] > \text{SFR} [200 \, \text{M}_\odot/\text{yr}] \]

Outflow Kinetic power ~ 6% AGN \( L_{\text{bol}} \) (as expected for a shock wave produced by radiation pressure onto the ISM)

Outflow on > 0.6 kpc scale
High velocity components are not centered on AGN. Both blue and red are offset by ~ 200 pc in the same direction.
AGN feedback in Mrk 231: mapping the CO OF

- A diffuse faint component north with +500 km/s (HCN also)
- Highest velocities are more compact
- Outflow is stratified
- Projected size ~ molecular disk size
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Mass outflow rate
\([M_{\text{Sun}}/\text{yr}]\)

Ekin rate
\([10^{44} \text{ ergs/s}]\)

Depletion time
\([\text{Myr}]\)

Stars older than \(~1\,\text{Myr}\) in the central kpc? (Lipari+2009)
To be verified by on going LBTI imaging on PAH to trace SF regions on 100 pc scale.

Feruglio+2014
AGN feedback in Mrk 231: mapping the CO OF

Mass outflow rate [M_{Sun}/yr]  Ekin rate [10^{44} \text{ ergs/s}]  Depletion time [Myr]

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Radial profiles

Mass outflow rate $[\text{Msun/yr}]$
Ekin rate $[10^{44} \text{ ergs/s}]$
Depletion time $[\text{Myr}]$
Mout/Mdisk

Feruglio+2014
Statistics of extended outflows

AGN outflow depletion timescale
<< star-formation depletion timescale

Problem:

\[ t_{\text{dep}} \ll \text{AGN timescale} !!! \rightarrow \]

observations of outflows should be rare!
They are ubiquitous instead...

Two possibilities:

1) Outflows are characteristic of a short phase during AGN evolution and samples are biased toward this phase (obscured AGN)

2) Outflows are cyclic phenomena. The ISM is first accelerated outward and heated. It then decelerates after cooling, raining back into the galactic disk: SF and accretion restarted

Cicone+2014
Remarkable correlation between AGN outflow rate and AGN bolometric luminosity: \( \frac{L_{\text{bol}}}{M_{\text{out}}} \sim 7.5 \times 10^{42} \text{ erg/s / M}_\odot/\text{yr} \)
AGN feedback models - I

AGN radiation launches a relativistic wind from very close in. The wind shocks against the surrounding gas and drives an outflow. If the mass of the black hole powering the AGN > $10^8 \, M_\odot$, the wind shock can propagate to large distances. The previously weak and cold, momentum-driven outflows become violent, energy-driven outflows, that can clear galaxies of their gas. *Energy conserving.*

Lapi, Menci & Cavaliere 2005, Blast wave model. King 2003, Zubovas&King 2014
Radiation pressure driven winds (momentum conserving):

If the outflow is momentum driven molecular gas may not reach escape velocity and falls back. $P_{\text{out}}/P_{\text{AGN}}<1$-3.

SF would not be strongly inhibited (Gabor & Bournoud 2014)

Dusty shells may reach escape velocity (thousand km/s, Thompson+2014).

$P_{\text{out}}/P_{\text{AGN}}<10$
Statistics of extended outflows

AGN outflow momentum rate $>>$ AGN radiation momentum rate

Most outflows energy-conserving

(but uncertainties are LARGE)
What is feedback?

- Do AGN outflows *clear* a galaxy from its gas
  or
- Do AGN outflows *regulate* the conversion of gas in stars, i.e. the SFR, by increasing the gas entropy?
Statistics of extended outflows
Statistics of extended outflows

higher the energy injected in the ISM higher the SFR and SFE!!
and higher the SFE higher the Eddington ratio!!

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Statistics of extended outflows

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Open questions & developments

• Need to image more AGN-driven outflows: High resolution and high sensitivity maps to assess the morphology of the outflows and how they compare to quiescent gas

• Dense gas phase (HCN, CS, ...) outflows (stars born from dense clouds)

    NOEMA / ALMA will tell

• Are outflows a short or a cyclic phase in AGN evolution?

• Desperately seeking more examples of quasar-mode feedback!

• How does feedback work? Clearing or regulation?
Assess whether the outflow is driven or not by a shock, to understand the energy transport mechanism from nucleus to disk.

Is the outflow energy-conserving? Is it powerful enough to heat/expel most molecular gas?

How:
X-ray and mm observations of outflows in the same source.
ALMA/NOEMA observations of UFO sources.
Athena systematic observations of sources with molecular outflows.
Open questions & developments

Unified scheme for AGN outflows

Are UFOs the relativistic wind launched by AGN radiation?
How are UFOs related to the molecular flows?
Systematic X-ray / mm studies are needed, Athena/ALMA?
Are ionised outflows and BALs co-spatial with molecular outflows? Or rather an evolutionary phase? (Zubovas & King 2013)
Optical/NIR IFU observations of sources with UFOs and BALs can tell