OBSERVATIONAL SIGNATURES OF AGN FEEDBACK

Dominika Wylezalek

[Johns Hopkins University]
• **Introduction:**
  
  • AGN Feedback
  • Observational Evidence

• Feedback signatures in powerful AGN at z ~ 0.5

• Feeding & Feedback in low-z AGN
Why Quasar Feedback?

Several relations between host galaxy bulge properties and black hole properties.

Idea of galaxy/black hole self-regulation.
released energy by BH \hspace{2cm} binding energy of galaxy

$0.1 M_{\text{BH}} c^2 \gg M_{\text{gal}} \sigma^2$

Lots of binding energy available, efficiencies of 1-5% are sufficient
INTRODUCTION

Galaxy Formation

Fig. 10. – The expected (red line) and observed (blue line) galaxy luminosity function. The discrepancies in the low- and high-mass ends is probably due to SN and AGN feedback, respectively. Figure from [49].

efficiency). As shown schematically in fig. 10, a single value can be calculated so that the observed and the theoretically predicted curves overlap at $M^\star$. However, their shapes are different, since stellar mass does not necessarily follow halo mass. Assuming a universal mass-to-light ratio leads to too many small galaxies, too many big galaxies in the nearby Universe, too few red massive galaxies at high redshift and too many baryons in galactic halos. There are additional problems, such as overconcentration and excessive cuspiness in simulated dark matter halos.

The resolution of all these problems must be related to the dynamics of baryons within the dark matter halos, and more specifically the feedback mechanisms that would lower star formation efficiency on various scales. Possible sources of feedback include supernovae, photoionization, massive stellar winds, tidal disruption, input from active galactic nuclei and cosmic reionization. Below we will discuss some of the issues related to feedback, focusing primarily on dwarf galaxies. A more complete treatment is given in several recent reviews [51, 49].

2. Supernova-driven winds. – One of the possible feedback mechanisms that may suppress star formation is galactic winds driven by the star formation process itself [52, 53]. After an initial population of stars has formed, a certain fraction of those stars (depending on the IMF) explode as supernovae, releasing large amounts of energy into the surrounding medium. If the outflow is accelerated to a velocity that is higher than the escape velocity of the galaxy, it is ejected into the IGM, suppressing the star formation rate. Such outflows have been detected in many systems and are believed to be the primary mechanism by which metals are deposited into the IGM [54].

Whether or not this process can significantly affect star formation efficiency depends...
Until recently:

Few observations of quasar feedback

Earliest evidence: radio jets, bubbles

Most quasars: radio-quiet, no powerful jets! Radiatively-driven winds?

Cattaneo+2009
Observations - IFU

Spectrum in every single pixel (spaxel)

credit: S. Todd, D. Pierce-Price
Observational Evidence
OBSERVATIONAL EVIDENCE

Recent detections of galaxy-wide outflows with high velocity dispersions in luminous quasars now seen by several groups

Liu+2013a,b
High-redshift (distant) powerful quasars with FWHM ~ 3000 - 5000 km/s

Zakamska+2016
The velocity field traced by the [OIII] emission is less clean than observed for the Hα emission in the quasar NLR.

Fig. 4. Map of the narrow component of Hα emission, which is likely the region where star formation is suppressed in the SE region where the strongest outflow is detected. This observation supports models invoking quasar feedback to quench star formation in massive galaxies at high redshift.

The outflow rate of ionized gas is estimated to be $4 \times 10^{43} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$, confirming that the latticings trace star formation and not new gas outflow. Both the high outflow velocity ($\sim 1000 \text{ km s}^{-1}$) and the strong outflow interacting with the host galaxy disk strongly suggest that the outflow is produced primarily in the NLR.

References

Cano-Diaz+2012

Balmaverde+2015


WHERE TO LOOK?
Where to Look?

- Physical size of 1 arcsec [kpc] (0.01, 0.10, 1.00, 10.00)
- Quasar space density (today = 1) (0.1, 1.0, 10.0, 100.0, 1000)

Evolution of quasar space density
WHERE TO LOOK?

- Low-Redshift
  - Structures resolvable: > 400 parsecs
  - Study: Detailed feedback processes such as wind launching in AGN host galaxies' centers.
  - Luminous quasars are rare!

- Intermediate/High-Redshift
  - Structures resolvable: > few kilo-parsecs
  - Study: Feedback processes on galaxy-wide and beyond scales.

- Physical size of 1 arcsec [kpc]

- Quasar space density (today = 1)

Dominika Wylezalek, LineA Webinar, June 1st 2017
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  - Peak epoch of quasar activity! Crucial feedback processes that shape the evolution of modern-day galaxies.

Minimum resolvable physical size by ground-based telescopes.

Quasar space density (today = 1)

Dominika Wylezalek, LINEA Webinar, June 1st 2017
WHERE TO LOOK?

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Dominika Wylezalek, LiNeA Webinar, June 1st 2017
Feedback in Powerful Quasars at z ~ 0.5
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Quasar Host Galaxies

Galaxy-wide outflows

Scattering cones

Luminous quasar host galaxies are bulge-dominated galaxies

High merger fraction

High star formation rates

Liu+2013a,b, Wylezalek+2016a, Obied+2016
FAST IONIZED GAS ON LARGE SCALES

[OIII] velocity dispersion: Gemini IFU

Host galaxy stellar light, HST yellow band
[OIII] Narrow Band with HST

1" ~ 6 kpc
but the non-parametric velocity width measurements are closely related to the FWHM with total flux, respectively. For a purely Gaussian profile, line widths are a function of velocity:

For each spectrum, this definition is used to compute the as a function of velocity:

Gaussian components to determine the cumulative flux et al. egy presented in e.g. the [OIII] emission line. We follow the measurement strat-

tical spectra are available for all objects in the type-2 AGN. For example, all sources are required to have a high minosities and ratios characteristic of ionization by a hidden

based on emission line properties, such as emission line lu-

presented by Reyes et al. Sky Survey (SDSS,

We primarily draw our type-2 AGN from the Sloan Digital

2008 [OIII] AGN. For example, all sources are required to have a high

minosities and ratios characteristic of ionization by a hidden

SFR

Zakamska+2015 47 sources (23 upper limits)

HerS 21 sources (15 upper limits)

H-ATLAS SDP 2 sources

12 sources (8 upper limits)

16 sources

HerS 23 sources (19 upper limits)

H-ATLAS SDP 2 sources (1 upper limit)

0 sources

UKIDSS 843 sources

UKIDSS 239 sources

Reyes+2008 887 sources

Good kinematics 568 sources

Good kinematics 2706 sources

SDSS-BOSS

Yuan+2016

2707 sources

Larger samples needed

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sSFR vs. Velocity Width

Strong negative correlation between sSFR and velocity width at high SFRs

Wylezalek+2016b
sSFR vs. Velocity Width

Strong negative correlation between sSFR and velocity width at high SFRs

Wylezalek+2016b
ssSFR vs. Velocity Width

- negative correlation between ssSFR and velocity width at high SFRs
- coupling between wind+gas is potentially strongest
- relative signatures of AGN feedback
- decrease of ssSFR driven by increase in stellar mass
- effect of galaxy potential negligible

Wylezalek+2016b
errors are Gaussian with zero mean and that the intrinsic strengths, i.e. at higher velocity widths of the [OIII] emission, are considered. For illustration, we highlight all sources with redshift-dependent lower mass limit. We elaborate on this relation test confirms a correlation with 99% probability in parameter space. As we have discussed in Section 3.3, the advanced linear regression are available through the astrolib IDL routines to use this analysis.

We do not detect a statistically significant correlation between sSFR and stellar mass in the UKIDSS survey. Part of the observed correlation could be driven by the redshift-dependent lower limit on stellar mass could introduce a dependence in the parameter space are on average of lower redshift than the intrinsic strength. We therefore highlight the all sources with stellar mass in the highest bin of SFR and sSFR in three bins of SFR:

- $\text{SFR} > 300 \text{ } \mu \text{L}$
- $100 < \text{SFR} < 300 \text{ } \mu \text{L}$
- $0. < \text{SFR} < 100 \text{ } \mu \text{L}$

We show the result of that linear regression, taking properly into account the upper limits on sSFR, in Figure 7.

Figure 7. The scatterplot of sSFR vs. velocity width of [OIII] (W90) for different AGN luminosity bins: low, intermediate, and high LAGN. The figure shows the distribution of galaxies with different sSFR and velocity widths, highlighting the grouping of points for each AGN luminosity bin.
FEEDBACK THRESHOLD?

Zakamska+Greene 2014

\[ L_{\text{Bol}} \text{(AGN)} \]

\[ w_{90}, \text{km/sec} \]

\[ 1000 \]

Dominika Wylezalek, LINEA Webinar, June 1st 2017
• one of the first direct observational proofs of AGN having a “negative” impact on galaxy evolution

• effect of wind-gas coupling important, at high SFRs can be neglected
SUMMARY 1

• one of the first direct observational proofs of AGN having a “negative” impact on galaxy evolution

• effect of wind-gas coupling important, at high SFRs can be neglected

Luminosity threshold for AGN feedback
How are Outflows Launched?

What is their contribution to galaxy evolution?
**FEEDBACK THRESHOLD?**

![Diagram showing the relationship between L_{Bol} (AGN) and w_{90} (km/sec)](Zakamska+Greene 2014)
Feedback Threshold?

\[ L_{\text{Bol}} (\text{AGN}) \]

\[ \sim 10^{45} \text{ erg/s} \]

\[ w_{90}, \text{ km/sec} \]

Zakamska+Greene 2014
FEEDBACK THRESHOLD WITH ManGA/GMOS

MaNGA - SDSS IV:

10 000 galaxies

What about the AGN in this sample?

A MaNGA target galaxy, 500 Myr away
The figure illustrates the relationship between bolometric luminosity ($L_{\text{bol}}$) and the 90th percentile velocity width ($w_{90}$) of an AGN. The data points represent a large sample of galaxies, with the MaNGA survey emphasized in red. The plot shows a significant correlation, indicating that AGNs with higher luminosities tend to have stronger outflows. This suggests a feedback threshold in galaxy evolution, where AGNs play a crucial role in regulating star formation and the growth of central supermassive black holes.
Figure 2: Our planned program will study the interaction of winds with circumnuclear environment in luminous AGN (filled pink stars), resolving scales from 300 pc to 2.5 kpc. In combination with less luminous AGN (grey diamonds) and highly luminous objects (grey circles), both available within our collaboration, we will 'bridge the gap' (depicted by the pink box) between high-L\(_{\text{bol}}\) and low-L\(_{\text{bol}}\) AGN and test the threshold model of triggering quasar feedback. This luminosity regime is largely untouched by previous observations. The here proposed targets will be complemented by MaNGA-AGN for which GMOS data are already at hand (open stars). Building a large sample of such sources is critical in achieving our science goals.

Figure 3: MaNGA observations of three of the here proposed targets, with example data products. The resolved BPT diagram show which regions are dominated by AGN, star formation or both. The sources show distinct BPT morphologies (from concentrated to extended to galaxy-wide). Enhanced \([\text{O}\text{III}]\) velocity dispersion (scale bar in km/s) that is related to the AGN BPT signatures suggest that the AGN is driving outflows in these sources. In the first object, the signatures are 'blobby' and unresolved, whereas the second object shows some elongated, possibly cone-like signatures. The third object shows galaxy-wide signatures. With Gemini, we will 'zoom into' the central \(3.5 \times 5\) arcsec (the Gemini field of view with suggested position angles is shown by the green rectangle in the BPT maps) of these targets to trace the origin of the large-scale disturbed kinematics.

~10\(^{45}\) erg/s

"Bridging the gap" with MaNGA-selected AGN
MaNGA AGN from FT and 2016B program
Low luminosity AGN with no/<1kpc outflows
Powerful quasars with extended outflows
Feedback threshold with ManGA/GMOS

Emission Line Ratios used as diagnostic for different ionization mechanisms

“BPT diagrams”: Baldwin, Phillips & Terlevich

lines are close in wavelength space (same extinction, can be observed together)

Pilot Project: 2 sources
• 1 bona-fide AGN
• 1 AGN-candidate
Feedback threshold with ManGA/GMOS

We therefore investigate if the morphology of the outflow signatures and morphologies. We find average values in the plane of the disk, low values below the plane of the disk range between 1\ kpc and 5\ kpc.

Blob Source

MaNGA \(v(H\alpha)\) (km/s)

GMOS \(v(H\alpha)\) (km/s)

MaNGA \(v(H\alpha)\) model (km/s)

GMOS \(v(H\alpha)\) model (km/s)

MaNGA H\(\alpha\) model residuals (km/s)

GMOS H\(\alpha\) model residuals (km/s)

offset (arcsec)

offset (arcsec)

offset (arcsec)

offset (arcsec)

offset (pixels)

offset (pixels)

offset (pixels)

offset (pixels)

offset (arcsec)

offset (arcsec)

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\(\Delta W\)
GMOS is i.e. typical bulk velocity of the detected [OIII] regions in is only about 2 kpc across, was not detected in the MaNGA data an indication that this structure is either shock- or AGN-ionized Figure 4.

are negligible), the blue- and redshifted residuals from GMOS reveal the bipolar nature of a kinematically decoupled structure in the part of the Blob Source, which is indicated by the red box in the MaNGA maps. The middle panels show the rotational model to the H100 spatially coincides with a region of high H150

100

50

0

−200

−100

0

100

200

offset (arcsec)

1.0

0.5

0.0

−200

−100

0

100

200

offset (arcsec)

50

150

5 kpc

1 kpc

outflow (arcsec)

5 kpc

1 kpc

offset (arcsec)

MaNGA v(Hα) (km/s)

MaNGA v(Hα) model (km/s)

MaNGA Hα model residuals (km/s)

GMOS v(Hα) (km/s)

GMOS v(Hα) model (km/s)

GMOS Hα model residuals (km/s)

Outflow Signature!

Wylezalek+2017

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Feedback Threshold?

Unbiased selection, large sample of AGN in MaNGA allows systematic analysis of outflow properties in relation to AGN properties, galaxy potential, environment ....
**Classifying AGN in IFU data is difficult!**

Figure 4. Example BPT maps and plots for three galaxies with high f\textsuperscript{AGN} + f\textsuperscript{LINER}[SII], but where the pixels are classified as AGN or LINER in the [SII]-BPT diagram are very close to the demarcation line. The bulk of such galaxies are blue, highly star-forming and of low stellar mass.

Figure 5. Visualization of how we measure d\textsubscript{BPT},i and d\textsubscript{BPT},j.

For each spaxel in the AGN or LINER region of the [SII] BPT diagram, we measure the distance d\textsubscript{BPT},i between the position of the spaxel in BPT space to the star formation demarcation line such that the d\textsubscript{BPT},i is minimal. We then compute d\textsubscript{BPT} by averaging the d\textsubscript{BPT},i of the 20% of the spaxels with the largest d\textsubscript{BPT},i.

4.2 Observed Galaxy Radii

A major part of both the initial and the refined AGN selection criteria are based on measuring AGN spaxel fractions. We apply this threshold that is only dependent on observed size to (i) minimize the contamination from galaxies that would pass our AGN selection criterion due to measurements based on only a few single spaxels (which might represent a large physical region) and (ii) allow for an easy application to the whole MaNGA sample in subsequent years. But due to the design of the fibre bundles, the required spaxel threshold of 15% in our initial AGN selection criterium and 10%/15% in our refined AGN selection corresponds to different spatial fractions depending on whether the source belonged to MaNGA primary sample (fibre bundle radius corresponds to ≈1.5 R\textsubscript{e}) or the secondary sample (fibre bundle radius corresponds to ≈2.5 R\textsubscript{e}). We therefore investigate to what extent this simple fraction threshold biases our sample selection.

Figure 8 shows the normalized distributions of observed galaxy radii R\textsubscript{obs} to the effective radius of the observed galaxy R\textsubscript{eff} for all galaxies in MPL-5 and the 746 initial AGN candidates and the 303 final AGN candidates. While the distributions between the whole MPL-5 sample and the initial AGN sample (blue) differed significantly (p-value = 0.001 based on a two-sided Kolmogorov-Smirnov test), the distributions between the final AGN sample (pink) and the whole MPL-5 sample are likely drawn from the same distribution (p-value = 0.83). This shows that our initial AGN selection the percentage-based spaxel threshold biased the selection towards smaller R\textsubscript{obs}/R\textsubscript{eff} and therefore to lower redshift sources. That led to the selection of many AGN candidates with only marginal signatures. The refined AGN selection criteria manage to circumvent this caveat and reproduce the overall MaNGA distribution well.
How many AGN have we been missing?

Figure 6. Example BPT maps and plots for three galaxies in our final AGN selection. In addition to the SDSS composite gri image, we show the MaNGA-based resolved [NII] and [SII] BPT maps and the corresponding BPT diagrams for each spaxel. The green circle illustrates the size of the 300 fibre that was used to obtain a spectrum of the galaxy in SDSS I-III. While the galaxy in the upper row had been classified as an AGN based on the single fibre observations prior to MaNGA, the galaxies in the middle and lower row had not been selected as AGN candidates based on the single-fibre spectra.

Figure 7. Normalized distribution of observed galaxy radii normalized by their $R_{\text{eff}}$ for all galaxies in MPL-5 (filled, grey histogram), initial AGN candidates (blue) and final AGN candidates (pink). While our initial AGN selection was biased towards galaxies with low $R_{\text{obs}}/R_{\text{eff}}$, the final AGNs overcome this bias. A two-sided KS test between the all MPL-5 distribution and the final AGN distribution suggests that the two distributions are drawn from the same underlying distribution.

Figure 8. Normalized distribution of the stellar mass for all galaxies in MPL-5 (filled, grey histogram), initial AGN candidates (blue) and final AGN candidates (pink). While our initial AGN selection was biased towards galaxies with low stellar masses, the final AGN selection peaks at $\log (M_{\ast}/M_\odot) \approx 10.4$, generally associated with the most [OIII]-luminous galaxies in the whole MPL-5 sample.

Reyes et al. (2008) have shown that the [OIII] luminosity is an indicator for the total bolometric luminosity of the AGN if an AGN is present in the galaxy.
HOW MANY AGN HAVE WE BEEN MISSING?

- **Histogram:**
  - x-axis: $\log(\frac{\sigma_{\text{kin}}}{\sqrt{M \cdot R_{\text{eff}}}})$
  - y-axis: Normalized N
  - Grey: all MPL-5
  - Pink: Final AGN candidates

- **Scatter Plot:**
  - x-axis: $\frac{\text{[NII]}}{\text{H}$
  - y-axis: $\text{H}$$\beta$
  - Colored points: Final AGN candidates

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SUMMARY

• one of the first direct observational proofs of AGN having a “negative” impact on galaxy evolution

• effect of wind-gas coupling important, at high SFRs can be neglected

• Evidence for AGN activity and outflows in previously unknown AGN
• How classify AGN in large resolved IFU surveys? Have we been missing an important component in galaxy evolution?

Luminosity threshold for AGN feedback, to be explored using unique combination of MaNGA + GMOS