Active Galactic Nuclei in 3D (Integral Field Spectroscopy): Feeding and Feedback Processes

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Motivation: feeding and feedback in AGN

- Nuclear activity: fundamental phase in galaxy evolution -> SMBH growth
- Feeding of SMBH is necessary to trigger nuclear activity
- Cosmological models without feedback do not reproduce galaxy luminosity function
- Low L end: feedback from supernovae
- High L end: feedback from Active Galactic Nuclei (Bower et al. 2012)
- Benson et al. 2003; Hopkins et al. 2006; DiMatteo et al. 2008

“Madau” plot
Credit: J. Silk
Goals: constrain feeding and feedback processes in AGN

- Although peak of activity in the Universe at z~2, feeding and feedback processes which occur on ~100 pc scales only resolvable in nearby galaxies

- SMBH grows via gas inflow -> (1) map and quantify gas inflows

- Bulge grows via formation of new stars in the nuclear region -> (2) map the circumnuclear stellar population and its kinematics

- Feedback regulates the growth of SMBH and bulge -> (3) map and quantify gas outflows
Data: Data cubes from Gemini IFUs

Optical: GMOS IFU
- FOV: 3.5" x 5" or 5" x 7"
- Sampling 0.2"
- PSF ~ 0.6"
- R~2500

Near-IR
NIFS + ALTAIR (adaptative optics)
- FOV: 3" x 3"
- Sampling: 0.04" x 0.1"
- PSF ~ 0.1"
- R~5500, Z, J, H, K
Inflows in NGC7213 (Schnorr Müller et al. 2014b)

- Sa, LINER/Seyfert 1
- GMOS-IFU
- 0.7 kpc x 1 kpc
- Nuclear spiral
- 0.6"=60 pc
Sample spectra NGC7213 (Schnorr Müller et al. 2014b)

- Stellar kinematics from absorption spectra (pPxf, Cappellari & Emsellem 2004)
- Gas kinematics from emission lines
Inflows in NGC7213 (Schnorr Müller et al. 2014b)

- **Stellar kinematics**: rotation, close to face on
- **Ionized gas kinematics**: rotation + streaming along spiral arms (inner 400pc); blueshifts in the far side and redshifts in the near side -> inflow
- **Mass of ionized gas**: $1.3 \times 10^8 M_\odot$; inflow rate: $0.4 M_\odot yr^{-1}$ at 300 pc, $0.1 M_\odot yr^{-1}$ at 100 pc
Inflow along nuclear bar in NGC3081 (Schnorr Müller et al. 2015)

- SABO/a, Sy 2
- GMOS-IFU
- 1.25 x 1.80 kpc
- 0.6" = 100 pc
- Nuclear bar (~1kpc)
Inflow along nuclear bar in NGC3081
(Schnorr Müller et al. 2015)

- Gas velocity field: rotation + distortions correlated with nuclear spiral and bar
- Subtraction of rotation model: large residuals -> inflows along the bar + compact nuclear outflow
- Total ionized gas mass: $3 \times 10^8 \, M_\odot$
- Ionized gas mass inflow rate along the bar: $\lesssim 0.1 \, M_\odot \, \text{yr}^{-1}$
Minor merger fueling AGN in Mrk509 (Fisher et al. 2015)

- Sy 1 galaxy at $z=0.0346$
- $1'' = 700$ pc
- Filament in [OIII] and continuum
- STIS spectrum of filament: redshift close to the nucleus: inflow?
- NIFS observations to check

Fig. 1.— *HST* FQ508N narrow-band image of Mrk 509 showing primarily [O III] emission. The filament can be seen to the right of the nucleus, extending from northwest to southeast before making a 90$^\circ$ turn toward the nucleus. Starburst activity can be seen in a ring around the nucleus at a radius of $\sim 3''$. The dashed box shows the $3'' \times 3''$ field of view observed with NIFS.
Mrk509 (Fisher et al. 2015): scenario

- Gas in the disk: rotation
- Infalling filament: blueshifts then decelerates and turns towards the nucleus
NGC2110  
(Diniz et al. 2015)

- SO, Sy 2
- FOV= 450 pc x 450 pc
- 0.1″=15 pc
- K-band spectra: stellar and H2 kinematics
- Channel maps in H$_2$ (R=5300)
NGC2110: centroid velocity

- Stellar velocity field: rotation
- H2 velocity field: rotation + streaming along \(-200\) pc spiral arms
- Subtraction of stellar velocity field \(\rightarrow\) inflow
- Closer to the center: outflow?
- Hot \((2000\text{K})\) H2 mass \(\approx 1400\ M_\odot\)
- Cold H2 mass (Mazzalay +12) \(\approx 9.9 \times 10^8\ M_\odot\)
- Surface density \(\geq 710\ M_\odot\ \text{pc}^{-2}\)
- Confirming more blueshifts in far side and more redshifts in near side -> inflows

- Hot H$_2$ mass inflow rate $\approx 4 \times 10^{-4} \, M_\odot \, \text{yr}^{-1}$

- Cold H$_2$ inflow rate $\geq 40 \, M_\odot \, \text{yr}^{-1}$
  (using conversion to cold $\geq 10^5$, Dale+05, Mazzalay+12)
Spiral arms within inner ~600 pc: blueshifts in far side, redshifts in near side. If gas is in the plane -> inflow

- Mass inflow rate: $\sim 4 \times 10^{-3} \, M_\odot \, yr^{-1} \times 10^5$ (Dale+05, Mazzalay+12) $\geq 400 \, M_\odot \, yr^{-1}!!!
Other inflows:

NGC1097 – nuclear spiral: Fathi et al. 2006

NGC6951 – nuclear spiral: Storchi-Bergmann et al. 2007

M81 – nuclear spiral: Schnorr Müller et al. 2011

NGC4051 – nuclear spiral: Riffel et al. 2008

NGC7582 – inflow from nuclear ring: Riffel et al. 2009

Mrk1066 – nuclear spiral + compact disk: Riffel et al. 2011


- Near-IR: H2 in inflow and/or rotation
**Outflow in NGC2110** (GMOS-IFU, Schnorr Müller et al. 2014a)

- SO galaxy
- 1″ = 160 pc
- Radio jet extending by ~4″ (~600 pc)

Line emission extending over the whole FOV (at least up to 800 pc)
Kinematics: Compact Outflow

Several kinematic components, main:

- Extended emission: illumination/ionization of gas rotating in the plane out to > 800 pc
- Outflow only in inner ~160 pc (barely resolved);
- Mass of ionized gas: $9.8 \times 10^7 M_\odot$
- Mass outflow rate: ~0.9 $M_\odot$ yr$^{-1}$
Outflows in NGC1386 (Lena et al. 2015)

- Compact outflow within 40pc, but extended emission up to the borders of the field at ~200pc; mass outflow rate: $\sim 0.1 \, M_\odot \, \text{yr}^{-1}$
- Kinematics of most extended emission: rotation in the galaxy plane $\rightarrow$ illumination of gas rotating in the plane, not outflow
Outflows in NGC 1068 (NIFS, Barbosa et al. 2014)

- Sb, Seyfert 2
- 500 pc x 500 pc
- 0.1" = 7 pc
- [Fell]: 250 pc from nucleus: broader than conical shape of [OIII] -> partial ionization zone;
- H₂: 100 pc (radius) off-centered ring
NGC1068 channel maps: [Fe II] and H$_2$

[Fe II]: outflows
- Velocities up to 800 km/s
- Mass outflow rate: $4 \pm 1$ M$_\odot$ yr$^{-1}$

H$_2$ (green): decelerated expansion in the plane
- $-200$ km/s < $v$ < $+200$ km/s
- Hot H$_2$ mass $\approx 29$ M$_\odot$
- Estimated cold H$_2$ mass $\approx 2.1 \times 10^7$ M$_\odot$
- Garcia-Burillo+14, ALMA: for 50 pc < radius < 400 pc, outflow in H$_2$ with mass $2.7 \pm 1 \times 10^7$ M$_\odot$
- Surface density $>100$ M$_\odot$ pc$^{-2}$
Other outflows

NGC5929 and NGC5899: Riffel et al. 2015

Mrk1066: Riffel et al. 2010

Mrk1157: Riffel et al. 2011

Arp102B: Couto et al. 2013

NGC5548: Schönell et al. 2015
Summary and Conclusions: feeding

- Inflows in nuclear spirals, bars and disks, capture of dwarf companion; sometimes observed in H\(^+\) and almost always in H\(_2\) (if not inflow, compact rotation);

- Inflow velocities 50 – 200 km/s; Inflow rates \(~0.1 – \text{few } M_\odot\text{yr}^{-1}\)

- Estimated total gas masses in inner kpc \(~10^7 - 10^9\) M\(_\odot\)

- Surface molecular mass densities: 100 – 7000 M\(_\odot\)pc\(^{-2}\) \rightarrow KS law \rightarrow SFR \sim 0.1 – 10 M_\odot\text{yr}^{-1}

- co-evolution of SMBH and galaxy
Summary and Conclusions: stellar population

- Young stellar population related to H$_{2}$ in NGC1068 (Storchi-Bergmann et al. 2012):

- Possible evolutionary scenario (Storchi-Bergmann 2001, Davis 2007, others):

  Mass inflow -> star-forming rings (with possible mild nuclear activity) -> nuclear activity (with intermediate age rings) ->

  Co-evolution in the near Universe: SMBH growth + bulge growth ($\sim 10^{-3} \ M_\odot yr^{-1} \times \sim 1 \ M_\odot yr^{-1}$)

8/10/15  Storchi-Bergmann – IAU Division J Meeting, Honolulu, August 10, 2015  25
Summary and Conclusions: outflows

- Outflows in ionized gas with velocities: 200 – 800 km s\(^{-1}\) and mass outflow rates of \(~\text{few } M_\odot \text{ yr}^{-1}\)

- Geometry:
  1. hollow conical/hourglass (Fisher+13: \(~1/3\) of AGN)
  2. Compact or unresolved (inner 100-200 pc)

- Possible evolution: compact bubble ("young" AGN) expanding to "open" conical/hourglass shape

- Scenario: most extended emission due to illumination of gas rotating in the galaxy disk; only inner part is outflowing -> possible overestimation of power of the outflow by 1-2 orders of magnitude if it is assumed that all the gas is outflowing
Summary and Conclusions: outflows

- Power of the outflow in ionized gas: $< 0.1\% \ L_{bol}$ in the near Universe $\rightarrow$ little effect on the galaxy (but maybe larger on other gas phases?)

- Future: expand studies to a complete sample including more luminous AGN $\rightarrow$ look for correlations of geometry/extent/kinematics/mass outflow rate with AGN luminosity (MaNGA SDSS-IV, GMOS-IFU, NIFS)