Extragalactic Molecular Outflows and Feedback

Eckhard Sturm (MPE)

Image credit: ESA / ATG medialab. Tombesi+2015
Some history

Mkn 231: November 9, 2009, OD=179, OBSID=1342186811 (SDP_esturm_3)
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The masses of supermassive black holes correlate almost perfectly with the luminosities, velocity dispersions and stellar masses of their host bulges (Magorrian+ 1998, Gebhardt+ 2000, Ferrarese & Merritt 2000)
Both star-formation and AGN activity show peaks at $z > 1$, when the bulk of the activity occurred behind dust. Is this because there is a physical link between star-formation in galaxies (several kpc scale) and SMBH mass growth (<pc scale, the so-called AGN activity)? Via some feedback mechanism? Or have galaxies and SMBHs simply co-evolved without directly influencing each other?
The observed faint-end and bright-end slope of the galaxy mass (or luminosity) function (as described by the Schechter function) is significantly different from the predicted slope of the dark matter halo mass function.
What are the controlling mechanisms?

- **Positive feedback:**
  Common feeding, e.g. in Mergers, ‘Secular’ disk instabilities and clumps / bars / nuclear spiral structures/ triggered star formation through winds/shocks from AGN and/or stars

- **Negative feedback:**
  quenching of star formation and starvation of BH, e.g. via tidal stripping, strong winds/outflows from AGN and/or stars

**Molecular mass dominates the outflow**

**Stars are formed from molecular gas**
Molecular outflows and feedback

- Tracers (OH, CO, CII)
- Evidence, statistics, simple correlations
- Outflow masses and energetics (masses, outflow rates, momentum, luminosities)
- Does it have an effect? (mass loading, depletion times)
- Source and mechanism (AGN and/or Star formation, momentum and/or energy)
Mrk 231; Fischer+2010, Sturm+2011
The Herschel outflow samples span a broad range:

- pre-merger ULIRGs
- late-stage ULIRGs
- „classic“ IR-faint QSOs
- hard X-ray selected BAT AGN

Fischer+ 2010 (Mrk 231),
Sturm+ 2011 (5 ULIRGs + NGC253)
Veilleux+ 2013 (38 ULIRGs + 5 PG QSOs)
Spoon+ 2013 (24 (fainter) ULIRGs)
Stone+ 2016 (+52 BAT AGN)
Massive molecular outflows detected in
- 70% of ULIRGs
- 9% of BAT AGNs

Inflow:
- 11% of ULIRGs
- 17% of BAT AGNs

Outflows ubiquitous in ULIRGs $\rightarrow$ not a pencil beam (radio jet) effect
(see also EWs)
What OH line profiles can tell us (without any modeling):

- P-Cygni → outflow

- Found in ~ALL ULIRGs (→ not a pencil beam effect, but large opening angles)

- Profile sub-structure --> more than one outflowing (+quiescent) component

- Various transitions of different energy levels: hints at geometry

- emission weaker than absorption → spherical symmetry not necessarily the best approximation, and extinction plays some role

- Outflow parameters (e.g. velocity, power) correlated with AGN properties → AGN likely the main driver of powerful molecular outflows in ULIRGs
Outflow velocity \( \sim L_{\text{AGN}} \)

\[
\text{outflow velocity } v_{84} \quad \text{[km/s]}
\]

\[
\log \left( \frac{L_{\text{AGN}}}{L_\odot} \right)
\]

Spoon, Farrah, Leboullier et al. 2013

Sturm+2011, Veilleux+2013, Stone + 2016: 43 ULIRGs and PG QSOs, 52 BAT AGN
Info Point – I  statistics and simple correlations

In a Herschel sample of ~50 ULIRGs and ~50 AGN: detections of massive molecular

outflows

in

70% of ULIRGs
9% of BAT AGNs

inf lows

11% of ULIRGs
17% of BAT AGNs

- Outflows ubiquitous in ULIRGs → not a pencil beam effect

- Outflow velocity \( \sim L_{AGN}, \quad v_{\text{max}} > 1000\text{km/s}, \)

- Outflow dominated by AGN, at least for luminous AGN

Modelling of OH line profiles can

- Further quantify molecular outflows:
  - outflow mass (mass outflow rate), depletion time scale, outflow momentum rate

Comparison to feedback models:

characterise as AGN or star formation driven
characterise if radiatively or momentum driven, coupling efficiencies, ...
Modeling and energetics

14 ULIRGs (different merger stages)

\[ L_{\text{AGN}} = (0.3 - 2) \times 10^{12} L_\odot \quad \text{(Eddington} \rightarrow \text{SMBH} = 10^7 - 10^8 M_\odot) \]

\[ \text{SFR} = 50-350 M_\odot/\text{yr} \]

OH 119, 79, 84, 65

González-Alfonso + 2017
Modeling and energetics

Radiative transfer code
(González-Alfonso & Cernicharo 1999)

González-Alfonso + 2017
Modelling:

- Radius and covering factor $r, f$
- Outflow mass $M_{\text{out}}$
- Outflow rate $\dot{M}_{\text{out}} = \frac{M_{\text{out}}}{v/r}$
- Mass loading $\eta = \frac{\dot{M}_{\text{out}}}{SFR}$
- Momentum flux: $\dot{P} = \dot{M}v$
- Mechanical luminosity: $\dot{E} = 0.5 \dot{M}v^2$
- Outflow masses: \( M = (100 - 2900) \times 10^6 M_\odot \)
- Mass outflow rate \( \dot{M}_{\text{out}} = 200 - 1500 M_\odot / \text{yr} \)
- Mass loading: \( \eta = \dot{M}_{\text{out}} / \text{SFR} = 1 - 10 \)
AGN- or Starburst-driven? Momentum-conserving or energy-conserving?

\[ \dot{P}_{\text{tot}} / (L/c) \]

\[ L = L_{\text{AGN}} \quad \text{or} \quad L = L_{\ast} \]

\[ \begin{align*}
\dot{P}_{\text{tot}} / (L/c) &< 2 \times L_{\text{AGN}} / c \\
\dot{P}_{\text{tot}} / (L/c) &< 3.5 \times L_{\ast} / c 
\end{align*} \]

\[ L_{\text{AGN}} \quad (L_{\odot}) \quad \quad \quad L_{\ast} \quad (L_{\odot}) \]

Starburst99 (Leitherer + 1999): starbursts supply a maximum momentum of \(~3.5 \text{ L}_{\ast}/c\)
(including ram pressure of winds and radiation pressure on dust grains)
(Heckman+2015)

AGN may supply a maximum momentum of \(~2 \text{ L}_{\text{AGN}}/c\)
The combined momentum rates from the starburst and the AGN may be able to drive the observed outflows in moderate cases. High momentum boosts (5-20) require energy-driven outflows.
Supernovae and stellar winds can provide a mechanical luminosity of up to \(~1.8\%\) of \(L_\ast\) (Leitherer + 1999, Veilleux+2005, Harrison+ 2014) of which less than \(\frac{1}{4}\) will go into bulk motion of the ISM \(\rightarrow\) energy-conserving winds from the starburst unable to drive the observed molecular outflows, at least in the strong outflow cases.

Energy-conserving bubbles created by AGN winds supply up to \(~5\%\) of \(L_{\text{AGN}}\) (e.g. King&Pounds 2015) with \(\frac{1}{2}\) going into bulk motion of the ISM (Faucher-Giguère & Quataert 2012)
Gas depletion time $t_{dep} = \frac{M(H_2)}{\dot{M}_{out}}$

Gas consumption time $t_{con} = \frac{M(H_2)}{SFR}$

$\frac{t_{con}}{t_{dep}} = 1.5 - 15^*)$

Mass loading $\eta = 1 - 10$

*) assuming continuous flow and no replenishment

Does it matter? (Aka can we convince Peter B.?)
Does it matter?

Warm, AGN-ULIRGs
Cold, SB-ULIRGs

SHINING (OH)  Fluetsch+ 2019 (CO)
Info Point – II Results from OH spectral modeling

- Combined momentum from AGN and starburst can drive the outflows in weak and moderate cases.

- The strongest outflows require energy-driven AGN mechanism

- $t_{\text{con}} / t_{\text{dep}} = 1.5 - 15$, Mass loading $\eta = 1 - 10$

- Best fits are found for decelerating or constant velocity fields


Caveats: OH-based outflow parameters like momentum, energy, mass loss rate require modeling with uncertain assumptions (geometry, OH abundance) (For and OH abundance study see Stone+ 2018)
Other molecular outflow tracers in the FIR

HF (J = 1–0) in NGC 253 (HIFI)

Outflow mass: \( M(\text{H}_2)_{\text{out}} \sim 1 \times 10^7 \, M_\odot \)
Outflow rate: \( \dot{M} \sim 6.4 \, M_\odot \, \text{yr}^{-1} \)
Consistent with OH and CO
Future of OH

Still some Herschel archival work to be done

ALMA, NOEMA: extend the Herschel OH studies to the high redshift Universe. e.g. OH 119 µm doublet is redshifted to the ALMA band 9 for galaxies in the redshift range $z \approx 2.5 - 3.1$, and to the ALMA band 7 for galaxies at $z \approx 5.8 - 8.0$. 
Future of OH

SPICA 0<z<2

IRAS 03158+4227
Mrk 231
IRAS 23365+3604

OH65—total
-1000 to 1000 km s⁻¹

1σ (t=2h)

Continuum—normalized

V (km/s)

IRAS 03158+4227
Mrk 231
OH65
LR (R=300)
t=2h

OH119—blueshift
-1000 to 0 km s⁻¹

1σ (t=4h)

Continuum—normalized

V (km/s)

CH⁺

IRAS 03158+4227
Mrk 231
OH119
HR (R=600)
t=4h

±σ

OH
Future of OH

SPICA 0<z<2

![Graphs showing the future of OH in the context of SPICA observations.](image-url)
But:

- no new Herschel observations,
- mm-interferometry of OH absorption at high z difficult
- SPICA not (yet) reality
- OH-based outflow parameters like momentum, energy, mass loss rate require modeling with uncertain assumptions (geometry, OH abundance)

→ Need complementary/alternative tracers
II) CO
Mrk 231

$1200 \text{ km/s}$

Feruglio+ 2010
IRAS F08572+3915

H-band image (Scoville et al. 2000).

Main outflow: biconical outflow with a large opening angle, inclined w.r.t. line-of-sight. \( \rightarrow v_{\text{max}} \) close to the maximum observed velocity in the outflow: 1200 km s\(^{-1}\).

The second redshifted outflow matches the description of an individual cloud 6 kpc away (\( \rightarrow \) AGN flickering).

Cicone, Maiolino, Sturm + 2014
Today

CO outflows in local galaxies:
~50 objects (NOEMA/ALMA)

(cp. Fluetsch+ 2019, Lutz+ in prep.)
Molecular outflow rate as a function of SFR, stellar mass, and AGN luminosity

Fluetsch+ 2019

~50 objects
Kinetic power of the outflow as a function of the AGN luminosity

Fluetsch+ 2019
Ishibashi+ 2018
Fraction of the molecular outflow that escapes the galaxy as a function of AGN luminosity

Assuming ballistic motion

Fluetsch+ 2019
The synergy and complementarity of OH and CO studies

In the local Universe, CO complements Herschel studies, providing the necessary spatial resolution to resolve the outflows using low-J rotational transitions of the CO molecule and other dense gas tracers (HCN, HCO+).

The OH observations provide cross-calibration and guidelines where to search for outflows, e.g. ULIRGs, sources with high far-infrared surface brightness ($\Sigma_{\text{FIR}} > 10^{11.75} \, L_\odot \, \text{kpc}^{-2}$, see Lutz+ in prep.).

→ Better characterization of spatial extension / outflow geometry, gas excitation, the total molecular gas mass involved in the outflows and the mass outflow rates.
Challenges & comparison of CO - OH

**OH:**
- wavelength needs space observatories (or high z)
- geometry,
- abundance (but see Stone+ 2018)

**CO:**
- separate outflow emission from host emission
- geometry
- conversion factor (CO-to-H2) (but see Cicone+ 2018)
Challenges & comparison of CO - OH

\[ M_{\text{out}} = v_{\text{out}} \frac{M_{\text{out}}}{R_{\text{out}}} \]

\[ M_{\text{out}} = 3v_{\text{out}} \frac{M_{\text{out}}}{R_{\text{out}}} \]

\[ M_{\text{out}} = v_{\text{out}} \frac{M_{\text{out}}}{\Delta R_{\text{out}}} \]

Lutz+, in prep.

See also Cicone+ 2014, Janssen 2016, Veilleux+ 2017
Challenges & comparison of CO - OH

- >80% of objects with OH outflow also show CO outflow (and vice versa)
- good agreement of outflow velocities

Lutz+, in prep., Gonzalez-Alfonso+ 2017
Challenges & comparison of CO - OH

Succesful cross-validation of OH P-Cygni and CO interferometric methods (independent/different assumptions and uncertainties, like geometry, abundance/conversion factor, identification of outflows...)

Lutz+, in prep., Gonzalez-Alfonso+ 2017
AGN „flickering“ – another complication

Some outflow energetics need stronger AGN in the past

- Rad. press.-driven
- Energy-driven
- Momentum-driven
- Add. outfl. phases

Low median flow time

Spatially resolved blobs

Fluetsch+ 2019

Lutz+, in prep.

Multi-phase studies

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<th>Outflow gas phase</th>
<th>Primary tracers</th>
<th>Average gas temperature, $&lt;T_{\text{gas}}&gt;$ (K)</th>
<th>Average gas density, $&lt;n_{\text{gas}}&gt;$ (particles per cm$^3$)</th>
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<td>Highly ionized</td>
<td>X-ray absorption lines</td>
<td>$10^6$–$10^7$</td>
<td>$10^6$–$10^8$</td>
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<td>Ionized</td>
<td>[O III]; Hα</td>
<td>$10^3$–$10^4$</td>
<td>$10^2$–$10^4$</td>
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<td>Neutral atomic</td>
<td>H i 21cm; NaID; [C II]</td>
<td>$10^2$–$10^3$</td>
<td>1–$10^2$</td>
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<td>Molecular</td>
<td>CO; OH; [C II]; H$_2$ infrared lines</td>
<td>$10$–$10^2$</td>
<td>$\geq 10^3$</td>
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Cicone+ 20018a, see also Tombesi+2015
Multi-phase studies

Fluetsch + 2019

See also Cicone + 2018a

Janssen + 2016, + 2019

H2: Rupke & Veilleux 2013a OSIRIS / Keck
Hα and Na I D: Rupke & Veilleux 2013b
GMOS/Gemini
Multi-phase studies

Herrera-Camus+ in prep.
CO at high redshifts
CO(3-2) in zC400528: an AGN-driven Outflow in a Typical Massive Galaxy at z≈2

Herrera-Camus+ 2019
CO(3-2) in zC400528: an AGN-driven Outflow in a Typical Massive Galaxy at $z \approx 2$

Herrera-Camus+ 2019
CO(3-2) in zC400528: an AGN-driven Outflow in a Typical Massive Galaxy at z≈2

Herrera-Camus+ 2019
OH as an outflow diagnostic

Advantages:
- P-Cygni or blueshifted absorption unambiguously indicate outflows
- Blueshifted absorption can be traced to low velocities, probing low-velocity outflows that may be missed from pure emission lines due to confusion with the line core
- Main outflow parameters can be quantified

Disadvantages:
- Historically: low spatial resolution
- Currently: For low z not observable with existing instrumentation, and difficult at high z
CO as an outflow diagnostic

Advantages:
- Strong emission
- High spatial resolution
- Currently one of the main topics for ALMA and NOEMA

Disadvantages:
- Emission ambiguous (outflow, inflow, turbulence, ...)
- Not sensitive to low velocity outflow (invisible under host galaxy profile) unless spatially resolved in imaging
- Not straight forward at high z (conversion of high-J CO to CO(1-0) and H2)
- Conversion factor

OH difficult at high z, too → is there an alternative?
III) [CII]
M82, velocity dispersion

Contursi + 2013
CII as tracer of (molecular) outflows

IRAS10565 CII
FWHM=856 km/s

Janssen+ 2016
CII as tracer of (molecular) outflows

- 22 SHINING ULIRGs
- 15/22 exhibit broad [CII] components
- All ULIRGs with broad [CII] also show an OH outflow: 13/15, one is an inflow, one OH non-detection due to S/N
- 13/16 OH outflow objects also show broad [CII]. Non-detections of [CII] mostly for objects with low outflow velocities

Janssen+ 2016
Outflow masses – OH vs. [CII]

Janssen+ 2016.
SDSS J1148+5152, $z=6.4189$

[CII]158μm
Maiolino + 2012
Cicone + 2015
IRAM

$\frac{dM}{dt} > 3500$ Msun/yr

Capak+2015, Gallerani+2016,
Pallottini+ 2016,
See also Riechers+2014
(z=5.3 SMG)
ALMA suggests outflows in $z \sim 5.5$ galaxies
Herschel OH outflow studies are an excellent example of a major result from a space mission that came (to some extent) as a surprise.

They:
- provided significant new insights regarding the existence, properties and physics of molecular outflows, thereby supporting models and our understanding of galaxy evolution (still ongoing)
- kick-started (sub-)mm interferometric studies by inspiration and by instructions where to look for outflows
- provided independent validation/calibration for outflow properties derived from (sub-)mm interferometry
- paved the way for SPICA by providing a key science case (z<2) and for future ground-based (high-z, OH, CO, CII) studies (NOEMA/ALMA)