Taking snapshots of the jet-ISM interplay with ALMA: the case of the CSS PKS 0023–26

Raffaella Morganti
ASTRON, Kapteyn Institute

Tom Oosterloo, Clive Tadhunter
Suma Murthy and many others....
Role of radio jets for feedback

Hundreds of kpc-scales

Maintenance mode: prevent cooling of gas: radiative inefficient radio AGN

hot gas/cavities
radio plasma

-200 kpc

Hundreds of kpc-scales
but the impact of jets starts already in the very inner regions and when the radio source is young!

Sutherland & Bicknell 2007
Wagner, Bicknell et al. 2011; Mukherjee et al. 2015
Role of radio jets for feedback

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Impact can be traced by gas in different phases, e.g. outflows common in warm ionised gas (especially in CSS/GPS), but the most massive component in cold gas

We use the cold molecular gas as tracer

Sutherland & Bicknell 2007
Wagner, Bicknell et al. 2011; Mukherjee et al. 2015
Complex multi-parameter space to explore!

- Radio power
- Evolutionary stage/age
- Multi-phase outflows and location
- Orientation jet/ISM

Our ALMA (and NOEMA) sample of GPS/CSS observed so far

High spatial resolution (~0.2 arcsec) to follow the molecular gas across the radio emission

See also talk by Suma Murthy (Friday's session)
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- **radio power**
- **evolutionary stage/age**
- **multi-phase outflows and location**
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PKS 0023-26 a young (CSS) radio galaxy....

PKS 0023-26 ($z = 0.321$): young but evolved powerful jet ($\sim 4$ kpc)
Also powerful optical AGN

FarIR bright and young stellar population $\rightarrow$ SFR $\sim 24$ $M_\odot$/yr

Redshift $z = 0.32188$

Chandra observations on-going (PI Siemiginowska)

X-ray observations

X-ray spectrum

Merlin 4.9 GHz

X-Shooter - Santoro et al. 2020

Optical, Ramos Almeida et al. 2013
PKS 0023-26 view by ALMA

- Mass of molecular gas: about $10^{10} \, M_\odot$
  - distributed on ~20 kpc, with tidal streams

- Large amount of molecular gas, accretion from companions and cooling of the hot halo: similar to cases found in clusters?

- Bright central region of molecular gas
  - piling up of gas or effect of higher excitation due to AGN (will require more transition to check this)

- Low brightness at the location of the lobes

Ideal system for the study of the impact of the (radio) AGN, but the kinematics of the gas had some surprises
• High velocity dispersion at the location of the radio lobes.
• Radio lobes tend to avoid regions rich in molecular gas or they have pushed it aside (seen in intensity and kinematics)
not fast outflows of molecular gas @lobes → possible reasons: density of the gas not high enough for a fast cooling + strong interaction from the powerful jet...

BUT

the high velocity dispersion at the location of the radio source suggests the jets/lobes are in the process of pushing the gas aside

Jet power \((4 \times 10^{46} \text{ erg/s})\) can provide enough energy....

Star formation in the host galaxy not yet strongly affected!
PKS 0023-26 and friends: what have we learned so far...

Complex multi-parameter space to explore!

radio power

evolutionary stage/age

multi-phase outflows and location

orientation jet/ISM

age (<10^6 yr)

radio power

Morganti et al. 2015; Oosterloo et al. 2017, 2019, Maccagni et al. 2017, Murthy et al. in prep.
Outflows of cold (molecular) gas in the inner (sub-kpc) region

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• Outflows of cold (molecular) gas in the inner (sub-kpc) region

origin of molecular outflows: jet interacting with dense clouds followed by fast cooling

Highest mass outflow rate (>400 M_☉/yr)
in the powerful radio source PKS1549-79
but outflows also in low power

Oosterloo, Morganti et al. 2019

ALMA
PKS 1549-79
~0.2 kpc

ALMA
PKS 1549-79
~0.2 kpc

Position-velocity plot of the CO(3-2) ALMA data of IC5063
Data
Modelling

B2 0258+35 - NOEMA CO(1-0)
Murthy et al. in prep.
See Murthy’s talk tomorrow
Properties of the outflows of molecular gas...

- **Physical properties** of the molecular gas affected by the interaction: high ratio CO(2-1)/CO(1-0) indicates high excitation and/or optical thin conditions in the region most affected by the jet.

  Kinetic temperatures in the range 20–100 K and densities between 10^5 and 10^6 cm^{-3} (best fit of ratio line transitions suggests a clumpy medium)

**Mass outflow rates: tens to a few hundred M_☉/yr**

**BUT**

Small fraction of gas leaves the galaxy: most of the gas raining back, fountain-like effect

**Impact of gas outflows limited even in objects with ideal conditions for AGN-driven (jet-driven) feedback: outflows cannot be the entire story!**
Not only outflows: changing the impact while evolving...

Jet further expands (PKS 0023-26): lower gas density (longer cooling times) $\Rightarrow$ jet drives mild shocks into the ISM, pushing aside the (molecular) gas, bubble-like structures $\Rightarrow$ this will affect the entire host galaxy when the radio source expands (next few $\times 10^7$ yr)

transition from outflows to maintenance mode $\Rightarrow$ heating of the ISM

Impact on the e.g. star formation may not be on the same time-scale as the AGN

see also Harrison et al. 2019
Scholtz et al. 2020

Adapted from Huseman et al. 2019
Some summary thoughts.....

- Evidence of **impact of jets in young** radio galaxies: observations consistent with predictions from jet simulations
- **Outflows** of cold (molecular) gas in the inner (sub-kpc) regions
- **Small fraction of gas** is leaving the galaxy, the rest “rains” back
  main effect: inject energy, turbulence, redistribute gas
- As the radio lobes **expand in the host galaxy** → mild shocks pushing aside the gas.

- Impact of jets possibly evolving/changing as the jet expands: from driving outflows in the first phase (sub-kpc) to “maintenance” mode (stop gas from cooling) when the jet reaches kpc scales
- This evolution needs to be considered - ideal for linking nuclear region to CGM
- Effect on star formation may be visible only on longer time-scales
- What will the X-ray observations tell us?