Radio jets and outflows of cold gas

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A complex interplay and the role of AGN

Galaxy formation by coalescence of smaller objects and by the accretion of gas directly from its environment => complication: **tight interplay between star formation/AGN activity and ISM of a galaxy and its surrounding IGM.**

Interplay (or feedback) incorporated in galaxy formation models, e.g., to reduce the number of massive galaxies forming and to explain the tight correlation between the mass of the stellar spheroid and that of the central black hole.

- Cooling of ISM/IGM fuelling the BH activity
- Energy output influences/stops this cooling
- Temporarily stop of the fuelling and of the central activity

**Exploring all this @ radio wavelengths**

- Role of radio jets?
- Role of cold gas?

Wagner & Bicknell 2011

Fabian et al.
Gas outflows: the cold component of gas may be the dominant one!

Gas outflows: common in AGN, originally found in UV/X-ray gas

More promising: **cold gas and effect of the radio plasma**

- Outflow of cold gas found in **HI and molecular** gas
- Mass outflow rates comparable with starburst winds
- The mechanism => location of the outflow coincident with bright radio features

**Started with the HI.......**

Broad (~1000 km/s) blueshifted HI absorption => signature of outflow
...now found also in molecular gas

Morganti et al. 2003, 2005
What did we learn so far?

- Cold gas relevant (mass, mass outflow rate...) in outflows: both atomic neutral and molecular found, possibly the dominant phase? **outflows as complex and multiphase structures**
- Location of the outflows: signature of the interaction between radio plasma and ISM
- Gaseous outflows often found in **young/restarted radio sources**: connected to the **evolutionary stage/duty cycle** of the sources?
- What is exactly going on? and what is the impact? => I hope to learn this here!

What next?
Outflows of HI & molecular gas: we keep on finding more .....  
(but by far not enough)

From ULIRG......

Mrk231
Large mass outflow rate from CO (>100 M$_{\odot}$/yr first case found, Feruglio et al. 2010)
Tentative detection of HI outflow (less massive ~10 M$_{\odot}$/yr)

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Depletion time:
~10 Myr (for Mrk231) and
~30 Myr (for NGC1266)

HI absorption (WSRT)

Mrk231 CO detection PdBI

Feruglio et al. 2010

HI absorption (WSRT)

broad component? comparable to CO

Morganti et al. 2012

CO outflow

CO detection PdBI

Mrk231

HI

NGC1266

CO

CO(1-0) IRAM PdBI

Feruglio et al. 2010

CO mass outflow rate ~ 13 M$_{\odot}$/yr

Alatalo et al. 2011

...to “normal” galaxies

Wednesday, 1 August 12
Radio-loud Seyfert IC5063: off-nuclear HI outflow

- First case discovered of fast outflow (700 km/s) of neutral hydrogen (Morganti et al. 1998, Oosterloo et al. 2000)
- One of the clearer examples of jet/cloud interaction: outflow at the location of the bright radio lobe

Galaxy rotation (HI emission)

Outflowing gas (HI absorption)
IC5063: HI, CO and ionised gas outflows

Outflow of molecular gas in addition to the HI (and ionised gas)

Mass outflow rate:
- HI gas ~ 12 $M_\odot$/yr
- Molecular gas ~ 8 - 40 $M_\odot$/yr
- Ionised gas ~ 0.08 $M_\odot$/yr

Depletion time: 10 Myr

- (kinetic) Energy flux ~$10^{42}$ erg s$^{-1}$
- Eddington luminosity $E_{\text{dot}}/L_{\text{edd}}$ ~$10^{-3}$ (few x $10^{-2}$ fraction of bolometric luminosity)
HI outflows in radio galaxies: location, location, location!

Broad, shallow absorption of neutral gas => outflow


WSRT

Broad absorption

$\tau \sim 0.38\%$

$N_H \sim 6 \times 10^{20}\ cm^{-2}$

for $T_{\text{spin}}=100\ K$

Deep absorption=> associated with dust lane

Haschick & Baan (1985), Beswick et al. (2002)
WSRT


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HI outflows in radio galaxies: location, location, location!

exact location?

Broad HI absorption identified with a fast HI outflow

Haschick & Baan (1985), Beswick et al. (2002)
3C293: new EVLA data

Confirmed broad absorption (> 1000 km/s) against the W lobe (very weak core at 1.4 GHz)

- Mass outflow rate $M_{\text{dot}} \sim 50 M_\odot/\text{yr}$
- (kinetic) Energy flux $\sim 10^{43}$ erg s$^{-1}$
- Eddington luminosity $E_{\text{dot}}/L_{\text{edd}} \sim 10^{-3}$ (few x $10^{-2}$ fraction of bolometric luminosity)

Low star formation rate ($\sim 4 M_\odot/\text{yr}$, Papadopoulos et al., 2010), this outflow is sufficient to quench star formation in the host galaxy.

Similar to what observed in nearby LIRGS/ULIRGS (e.g. Feruglio et al., 2010): outflows are present over a large amount of the AGN’s lifetime.

Consistent with the high excitation CO lines $\Rightarrow$ induced by shocks in jet-ISM interaction (Papadopoulos et al., 2008, 2010).
Outflows of HI & molecular gas: we keep on finding more ….

A young, restarted (?), farIR bright radio source: 4C12.50

- Mass outflow rate $M_\text{dot} \sim 10^{-20} M_\odot/\text{yr}$
- BH mass $\Rightarrow 6 \times 10^7 M_\odot$ (Wu 2009)
- (kinetic) Energy flux $\sim 10^{42}$ erg s$^{-1}$
- Eddington luminosity $E_\text{dot}/L_{\text{edd}} \sim 10^{-4}$ (few x $10^{-3}$ fraction of bolometric luminosity) - Morganti et al. (2004)

VLBI observations to locate the broad HI absorption...
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Recently detected CO (Dasyra & Combes 2012) comparable with HI

VLBI observations to locate the broad HI absorption...
VLBI results revealing the location of the HI

4C12.50 - young radio loud source, ULIRG

Recently detected CO (Dasyra & Combes 2012) comparable with HI

H I mass of a few times $10^5$ to $10^6$ $M_\odot$

50 mas ~100 pc
VLBI results revealing the location of the HI mass of a few times $10^5$ to $10^6$ $M_\odot$.

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4C12.50 - young radio loud source, ULIRG

Fogasy et al. in prep

about 1000 km/s blueshifted

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VLBI results revealing the location of the HI outflow occurring ~100 pc from the nucleus.

Jet interacting with a rich, clumpy medium?

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What the theorists predict (on the small scales)

- Radio jet can provide a mechanism for producing **fast gaseous outflows**: coupling with all phases ISM and effective on large scales.
- Cocoons around the jet (shocked/disturbed gas over a large region)
- Focus on the effects of the **first phase (or restarted phase) of the radio source**

2D and 3D simulations: jets interacting with inhomogeneous medium, (Sutherlands & Bicknell et al. 2007; A.Wagner & Bicknell 2011)
Outflows and connection to the evolutionary stage of the sources?

All our detections so far are young radio sources or recently restarted clearing up the gas in the central regions.

Low surface brightness, extended radio continuum from a previous phase of activity.

... and many more
What next? ....

Quantify the relevance of jet-driven outflows for galaxy evolution
Explore the apparent connection between phase in the life cycle of radio AGN and presence of gas (and outflows?)
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- Radio jet acting in the first (or in a restarted) phase of activity: how often is this happening? => **wide field search at low frequencies to find signatures of “relics” with e.g. LOFAR**

- Deep observations to trace the kinematics of the HI => using stacking while waiting for SKA! => rare objects => **large-area search with e.g. Apertif**

- Molecular gas with e.g. ALMA
How often a radio source restarts....

Looking for signatures of this in LOFAR images....

LOFAR 60 MHz - 6h
3x3 deg, rms 20-30 mJy/b
Shulevski et al.
When everything else fails: using stacking we can reach interesting limits....

Example: WSRT data Lockman Hole

continuum down to 10 microJy (more than 6000 radio sources)
thanks to the broad band => HI for free up to redshift ~0.1
SDSS spectra for stacking
Using stacking to characterise the gas content in radio and non-radio sources

STACKING RED GALAXIES (0.06<z<0.09):
- HI easily detected in active (LINERS)
- No HI in “inactive” objects

The presence of HI absorption has not been yet investigated: those systems are rarer => larger search area required!

Gereb, Oosterloo, Morganti et al. in prep
Main results:

• outflow of atomic and molecular gas found in a **growing number of radio sources**: outflows as complex and multiphases structures
• **location** better known in some case
• the **cold gas** appears to be the **dominant component** in jet-induced outflows despite the high energies dumped in the ISM by radio jets

For the (near) future:

• **wide-field search at low frequencies to find signatures of “relics”**
• search for HI absorption and stacking to improve sensitivity (and look for the presence of outflows)