PROCEEDINGS OF SCIENCE

Outflows, feedback and jets

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The mechanism of energy feedback plays a key role in the modelling of structure formation and in reproducing the properties of local massive galaxies (e.g. the black-hole spheroid mass relationship and the bright-end of the galaxy luminosity function). The energy released by the active nucleus is one of the ways to generate such a feedback and gaseous outflows are one signature of such mechanism in action. I will review some of the recent results on the study of AGN-driven outflows in Seyfert galaxies, QSO and other AGN. These outflows can be radiatively driven or mechanically driven by the action of radio jets/lobes. Here, I present the status of searching for outflows in AGN using data taken in different wavebands and I will report on some recent examples where the effects of radio jets are clearly visible. Finally, I will discuss the possible impact that all this has on evolution of the host galaxy.

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1. Introduction: why AGN feedback?

The complex interplay between different constituents of galaxies has proven to be a major stumbling block for the success of models of structure formation. In fact, the balance between accretion and ejection of gas determines the growth and evolution of a galaxy (Silk & Rees 1998, di Matteo et al. 2005, Hopkins et al. 2005). Accretion triggers the formation of new stars and the growth of the central massive black hole (BH). In return, however, the energy released by star formation and nuclear activity (AGN) has strong effects on the gaseous medium in and around a galaxy. This activity can create massive outflows of gas with the effect of quenching the formation of stars and the central activity. This mechanism of energy *feedback* has now been recognized as key to successfully modeling structure formation and galaxy evolution (Silk & Rees 1998, di Matteo et al. 2005). However, particularly important in making feedback effective is also how the energy released couples with the interstellar medium (ISM) in the galaxy (see e.g. Wagner et al. 2011, 2012). A variety of mechanisms acting on a variety of scales are needed and have been proposed to do the full job. The radiative output of the accreting BH can heat the gas and/or expel it via radiation pressure (radiative feedback). Alternatively, if significant AGN power emerges in winds or jets (kinetic feedback), the resulting heating and momentum flow provide the link. Either form of interaction can drive gas out of a galaxy or at least prevent it from cooling rapidly (Silk & Rees 1998; Fabian 1999; for a review of the observational evidence see Fabian 2012). The former will clear the central regions from gas that could otherwise contribute to the BH growth or be converted in stars. Thus, *gas outflows* are one of the main signatures of feedback in action and, because of this, they are actively studied at different wavelengths (see Fabian 2012).

Finally, large radio jets would work on larger scales: they would interact with ISM/IGM and prevent the cooling of the hot gas. The presence of X-ray cavities has been recognized as a signature of such interaction. Although mostly found in cluster galaxies (McNamara & Nulsen 2012) they are now seen also in isolated objects (see e.g. Croston et al. 2007).

In recent studies, the idea has been suggested that a so-called *radio mode feedback* is operating thanks to radio jet/lobes heating of the gas and that this mode is seen mainly in low-redshift massive galaxies. A second mode, the so-called *quasar mode* is dominated by high-velocity winds driven by the radiation field of the AGN and this would mainly work in in high accretion rate objects. However, it is very unlikely that these two phenomena are so well separated. *Signatures of both mechanisms are observed in many cases and their effectiveness will also depend on the coupling with the ISM and between pc and kpc scale to be effective.* Understanding the relative importance of all these mechanisms is a goal of many recent studies.

Here, we focus on the presence and characteristics of outflows (Sec.2 and 3) and, in particular, on the effect of radio jets and the characteristics of outflows driven by radio jets (Sec.3). The possibility that some of these outflows are related to a particular phase of the radio source (Sec. 4) makes the impact of the radio-loud phase of activity even more important because of the possibility of this activity to repeat during the life of a galaxy. Finally, we will comment on what is the impact of all these outflows compared to the requirement from numerical simulations (Sec. 5).

2. From X-ray to optical, outflows on all scales

Gas outflows observed in AGN are complex and multiphase. Here, we first review some of the tracers of these outflows - the UV, the X-ray absorption lines and the optical/IR lines - leaving the tracers studied at radio frequencies (HI absorption and CO lines) to the next session. Many studies have been focused on these outflows and here we will mention only some representative cases. Up to very recently, outflows were mainly traced using ionised gas (see e.g. Crenshaw, Kraemer & George 2003, Nesvadba et al. 2007, Holt et al. 2009, Reeves et al. 2009, Tombesi et al. 2012, Harrison et al. 2012). The effects of these outflows are often confined to the very nuclear regions and the associated mass outflow rates are relatively modest (see e.g. Holt et al. 2011). However, they can still provide in many cases a significant component to the feedback.

The very inner regions as seen by X-ray - Ultra-fast outflows (UFO, Tombesi et al. 2012 and refs. therein) are highly ionized and mildly relativistic outflows observed in X-ray in Fe K line. They have been found in a large number (> 40%) of Seyferts and BLRGs (e.g. NGC4151) and also in radio sources (3C111). The characteristics of the outflows derived by these observations (Tombesi et al. 2012) can be summarised in: their distance from the BH is in the range ~ 0.0003-0.03 pc that makes them likely connected with accretion disks and their mass outflow rate is ~ 0.01 $M_{\odot}$/yr and a mechanical power of 10^{42-45} erg/s. These massive, wide angle and intermittent outflows have a mechanical power >>0.5% L_{bol}. These values can be compared to what required by numerical simulations (see Sec. 5).

Moving outwards: the UV and X-ray results - For a complete picture, it is important to trace outflows at various distances. Blueshifted UV (C IV, N V) absorption features and X-ray "warm absorber" with higher ionization lines (OVII, OVIII) component have been detected in ~60% of Seyfert 1 galaxies (Crenshaw & Kraemer 2012). The outflow velocities in Seyfert 1 are up to 2000 km/s while in QSO-BAL, the velocities are up to 25000 km/s. The UV absorbers show variable ionization and by constraining the location, the outflows must originate outside the inner accretion disk. The total kinetic luminosity is estimated in the range 0.5-5% of the bolometric luminosity (Crenshaw & Kraemer 2012).

Optical/IR on kpc scale - Outflows of ionised gas on kpc scales (emission lines) observed in the optical/IR are relatively common in AGN and there is a vast literature available (see e.g. Tadhunter 2008, Harrison et al. 2012).

In Seyfert galaxies, radial velocity offsets, i.e. blueshifted features of [OIII], are observed in their narrow-line regions in about 35% of the cases (while redshifted offset is detected in 6%). This has been explained as a combination of outflow of ionised gas and effects of extinction (see e.g. Crenshaw et al. 2010).

Observations using Integral Field Units (IFU) are now giving an even more complete - but also more complex - view of the kinematics of the ionised gas. Near-IR/optical IFU studies of NLR

in nearby Seyferts reveal the presence of outflows in a number of objects on scale of 100 pc (Storchi-Bergman 2012 for an overview, Riffel & Storchi-Bergman 2011).
However, in some cases, the overall kinematic of the gas can only be explained by the combination of rotation/outflows/infall. Even more, different lines appear to trace different phenomena. For example in the case of NGC1068, the [FeII]1.2/1.6 μm lines appear to be a good tracer of outflow while H_2 seems to be a tracer of infall. Similarities with the radio emission are observed (suggesting interaction between these two process) but they are not perfect, suggesting that other processes are also at work to influence the kinematic of the gas. The measured mass outflow rates range from 0.5 to few $M_\odot$/yr. For more details on the well study case of e.g. NGC1068 see Storchi-Bergman et al. (2012).
Finally, outflows in NLSy1 are traced by [OIII] (see Komossa & Xu 2007). The presence of outflows is instead not so clear in extended emission-line regions (EELR) of QSO (Fu & Stockton 2009).

3. Exploring feedback at radio wavelengths: outflows of cold gas

At radio wavelengths, one can trace the presence of radio jets and investigate whether they affect the kinematics of the gas. That the radio jet can influence the kinematics of the gas is known already since a long time, for example from the study of the ionized gas in radio-loud Seyfert galaxies (see for a recent overview e.g. Rosario, Whittle et al. 2008 and ref. therein).
In addition to this, cold component of gas (atomic neutral hydrogen, HI, and molecular gas) can be observed at radio wavelength. These components were not considered as the best tracers for outflows but this has changed in the last years following the discovery of massive outflows in HI and molecular gas (e.g. Morganti et al. 2005a, 2005b, 2010; Feruglio et al. 2010, Alatalo et al. 2011, Dasyra & Combes 2011, 2012). In a number of objects, radio plasma jets have been suggested to play the dominant role in driving the outflows. Indeed, in some cases (see e.g. Morganti et al. 2005b, Oosterloo et al. 2000), the location of the outflow appears to be clearly co-spatial with prominent radio features (e.g. hotspots). This has also been independently confirmed by observations of the ionized component of the gas. Radio jets can indeed provide a particularly suitable and fast way of transporting the energy because they couple efficiently to the ISM/IGM and produce fast outflows from the central regions as required from feedback models (Wagner & Bicknell 2011,

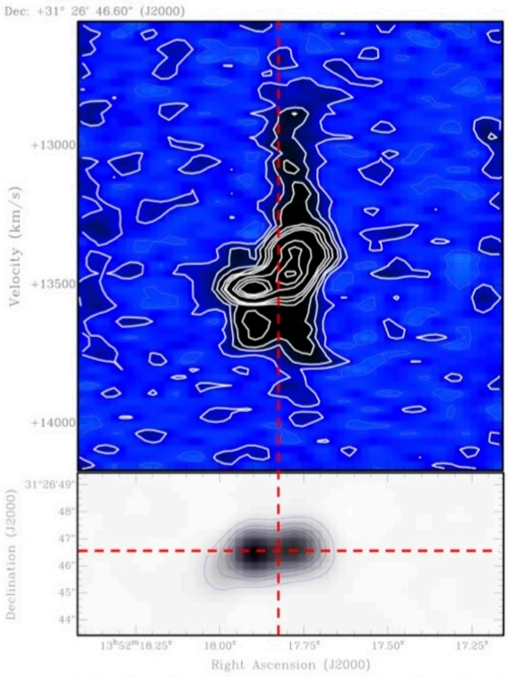

Figure 1 - Position-velocity plot (above) illustrating the location of the blueshifted, extremely broad (> 1000 km/s) HI absorption in 3C293. The continuum image (below, at 1arcsec resolution) illustrates the location of the absorption against the W lobe (Mahony et al, in prep).

Wagner, Bicknell, Umemura 2012).

A nice example of this is the case of the radio galaxy 3C293 where recent VLA observations have confirmed the location of the broad HI outflow discovered with the WSRT (~1000 km/s blueshifted compared to the systemic velocity, Morganti et al. 2003). The HI outflow extends up to ~0.5 kpc from the radio core (see Fig. 1 and Mahony et al. in prep). A mass outflow rate of ~50 $M_\odot$/yr has been derived. This outflow is likely the result of the interaction between the jet and the rich ISM of this galaxy.

An other example of this phenomenon is the radio-loud Seyfert 2 galaxy IC5063 that represents one of the best cases of a fast jet-driven HI (and ionized gas) outflow, observed located at the site of a radio-bright feature about 0.5 kpc from the nucleus (Morganti et al. 2007). In this galaxy, a prominent blueshifted wing is observed in the CO(2-1) spectrum obtained using APEX (Morganti et a. 2013). It is possible that the blueshifted part of the molecular gas is associated with the same outflow observed in HI and ionized gas, originated by the interaction of the ISM with the radio jet. The outflow of molecular gas is characterized by an H_2 mass of the outflowing component of between 2.25 +/- 0.70 x10^7 $M_\odot$ and 1.29 +/- 0.40 x10^8 $M_\odot$ and a mass outflow rate between 22 and 129 $M_\odot$/yr (Morganti et al. 2013). This – and the results obtained in other objects - confirms that this component of molecular gas may indeed be the dominant component in outflows driven by the nuclear activity.

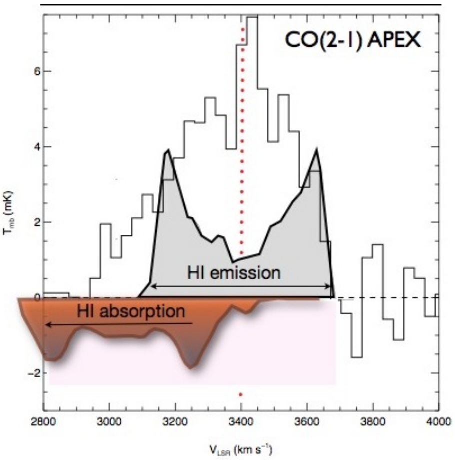

Figure 2 *- Profile obtained from the APEX CO (2-1) observations of IC5063. The profile is extremely broad (almost 800 km/s FWZI) and asymmetric showing a pronounced blueshifted "wing". The profile reaches velocities well outside the range covered by the regularly rotating large-scale gas disk observed in HI. The bluewards "wing" of the CO(2-1) profile covers velocities similar to those of the HI outflow detected in absorption (Morganti et al, 2013).*

The work on 3C293 and IC5063 and other objects (see e.g. Morganti et al. 2010) illustrates how important is to be able to locate the site where the outflow is occurring.

4. Once in a lifetime or repeated events?

In the case of the radio sources, a number of studies have proposed that the activity is recurrent (see e.g. Saikia et al. 2007). Furthermore, an intriguing relation between the presence of outflows and the stage in the life of the radio source has been suggested by the tendency to find HI and molecular gas outflows in young or recently restarted radio AGN (see e.g. Morganti et al. 2005). The presence in young radio sources of an high rate of outflows (of warm and cold gas) is explained by the fact that young jet have to make their way in the dense circumnuclear medium left over from the process that triggered the activity. This is expected from models of galaxy formation and has been confirmed by detailed studies e.g. in the case of PKS 1549-79 and the young radio source and far-IR bright 4C12.50 (Holt et al. 2006, 2011 respectively). The similarities suggested between some of these objects (and in particular PKS 1549-79, Holt et al. 2006) and NLSy1 is also intriguing. Also interesting is the high detection rate of outflows of ionised gas and high fraction of LoBAL found in radio selected, dust-reddened Type 1 QSO (Urrutia et al. 2009). These red QSO have also proposed to represent an early stage in the lifetime of the quasar. The detection of such a high fraction of broad absorption lines (BAL) could indicate that the quasar is in a young phase in which quasar feedback from the BAL winds is suppressing star formation in the host galaxy.

Unfortunately the statistics about the evolutionary stage of a radio source, its effect of the ISM and the relation with the presence of outflows is, at present, very limited. If this trend is confirmed once larger samples will be available, this would be extremely interesting as it would be consistent with what expected by theoretical models of feedback. Interestingly, if some of the radio AGN are due to triggering from gas cooling from the IGM (as suggested both from the study of the emission lines and from the study of the cold gas), then we should expect to see recurrent activity being relatively common and the relic of the past phase(s) of activity revealed by the coming surveys at low frequency (e.g. LOFAR, see Shulevski et al. these proceedings).

5. What is the impact?

As mentioned at the beginning, in recent years AGN feedback, in the form of quasar-driven outflows, has been relied upon to explain a number of observed relations. Currently, the majority of AGN feedback models require a significant amount of the available accretion energy to power the outflows (~5-10%; e.g. Di Matteo et al. 2005; Booth & Schaye 2009). If this were the case, the characteristics of most of the outflows discussed here would suggest that not a large enough fraction of the accretion power of the black hole is thermally coupled to the circumnuclear gas. The possibility of a more complex, "two-stage" action on the ISM clouds has been proposed by Hopkins & Elvis (2010). According to this model, the diffuse outflows would produce mixing/stretching deformation of the ISM clouds, increasing the effective cross-section. According to this model, a much lower fraction (0.5%) of the accretion luminosity would be needed to affect the host galaxy. This is much more consistent with the values obtained from various observations, as described in the previous sessions.

6. Conclusions

Gaseous outflows are common on the nuclear/small scales (up to kpc) of many AGN. These outflows have complex and stratified structure: gas in very different phases – but with similar kinematics - takes part to the outflow. Outflows of cold gas (HI and molecular) have become very interesting because of the mass they carry and the impact they may have on the evolution of the host galaxy. Mass outflow rates up to a few $M_{\odot}$/yr have been observed in warm, ionised gas while higher values (up to ~ 50 - 100 $M_{\odot}$/yr) have been derived for cold gas. Clear cases where the outflows are driven by the interaction between the radio jet and the ISM have been

found. Interesting, cold gas can be found associated with this interaction. New radio telescopes (including ALMA) will provide interesting insights in all this in the near future.
To understand the exact relevance of these outflows for the evolution of the host galaxies, more detailed theoretical models will need to be developed following e.g. the “two-stage” model proposed by Hopkins & Elvis (2010).

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