Jet Interactions and their Role in the Structural Evolution and Feedback

Lounging Galapagos sea lions, Red Mangrove Inn

Extragalactic jets from every angle
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An overview of jet-mode AGN feedback and the prospects for studying its cosmic evolution with LOFAR

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Abstract. Chandra revealed cavities in the hot atmospheres of many nearby clusters. These cavities are tracers of a strong coupling between the relativistic plasma in radio sources and the cooling, thermal gas in clusters. They demonstrate clearly that the AGN affects the cooling gas that leads to star formation and galaxy growth and allow a direct measurement of the bulk of the AGN's power. Together with radio data, the cavities allow us to derive scaling relations between mechanical (cavity) and radio power that can be used to estimate the AGN feedback power when direct measurement of the cavities is not possible. We review the importance of such relations for extending current studies of feedback with new and upcoming radio telescopes such as LOFAR and SKA.

Keywords. X-ray: galaxies: clusters, cooling flow, high redshift, radio continuum: galaxies

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1. Introduction

One of the principal aims of astronomy is to understand how galaxies form and evolve. It is now well established that almost all galaxies host a supermassive black hole (SMBH) at their center, the mass of which scales with the mass of the galaxy's bulge (Magorrian *et al.* 1998; Ferrarese & Merritt 2000). These SMBHs should have a significant influence on their host galaxies (and larger group or cluster environment), since the energy released in the formation of a SMBH is much larger than the binding energy of a galaxy. Indeed, there is considerable evidence that SMBHs, through feedback of energy from powerful outbursts from active galactic nuclei (AGN), might interact with and influence their host galaxies and clusters and likely might play an important role in regulating their growth (Ciotti & Ostriker 1997; Fabian 2012). The fuel for the AGN is supplied through the accretion of matter onto the SMBHs (Rees 1984) from gas injected during galaxy formation mergers or from cooling gas from the hot atmospheres of massive galaxy groups and clusters. The AGN transform the reservoir of mass that falls into the SMBH into radiative and mechanical energy, which in turn heats the cooling material. This cycle represents the *feedback loop*, such that increased cooling leads to greater accretion onto the SMBH that in turn leads to increased energy output from the AGN and a decrease (and hence regulation) of the cooling. However, many details of this feedback cycle are still poorly understood, particularly in distant systems where the largest galaxies are still forming. Powerful tools for studying these details have emerged in the last decade (e.g., *Chandra* and *XMM-Newton*) and will emerge in the coming decade (e.g., LOFAR, eROSITA, and SKA), making this a pivotal time in AGN studies.

AGN Feedback Modes. From a feedback perspective, AGN can be divided into two broad categories based on the accretion efficiency (the ratio of energy released to rest-mass accreted energy): jet-mode and radiative-mode AGN (for reviews see McNamara &

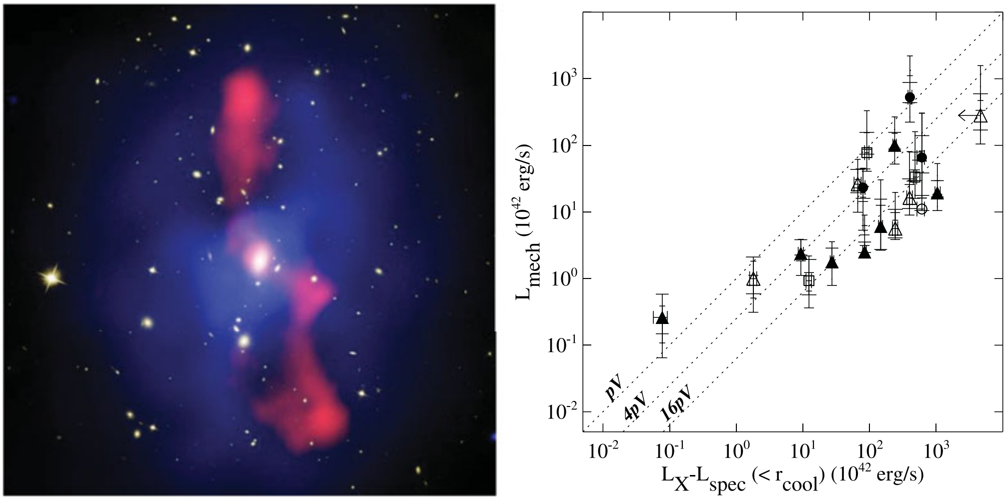

Figure 1. *Left*: An example of a cavity system, MS 0735+74, at $z = 0.216$ (McNamara *et al.* 2005). The radio emission, shown in red (Bîrzan *et al.* 2008) and the X-ray emission, shown in blue, are overlaid on an HST optical image. (*credit*: X-ray: NASA/CXC/Univ. Waterloo/B. McNamara; Optical: NASA/ESA/STScI/Univ. Waterloo/B. McNamara). *Right*: Cavity power of the center AGN vs. the total X-ray luminosity minus the spectroscopic estimate of the cooling luminosity (the cooling that needs to be offset by heating). The diagonal lines denote $P_{\rm cav} = L_{\rm ICM} - L_{\rm spec}$ assuming pV, $4pV$, or $16PV$ as the total enthalpy of the cavities (Bîrzan *et al.* 2004).

Nulsen 2007; Fabian 2012; Alexander & Hickox 2012; Heckman & Best 2014). A radiative-mode AGN occurs when the SMBH accretes at rates close to the Eddington limit. In this case, a radiatively driven process is thought to take place through galaxy outflows in ultra-luminous infrared galaxies (e.g., Rupke & Veilleux 2011) and quasars (QSOs, Feruglio *et al.* 2010; Villar-Martín *et al.* 2011). From the radio perspective, AGN can be separated in radio-loud (RL) AGN and radio-quiet (RQ) AGN., but the physical separation between the two categories is still unclear (e.g., star forming processes, BH spin, BH mass, etc.; Dunlop & McLure 2003; Tchekhovskoy *et al.* 2010; Padovani *et al.* 2011). The RL AGN of the radiative mode are also known as high-excitation radio galaxies (HERGs) and have strong QSO and Seyfert-like lines (Hine & Longair 1979; Best & Heckman 2012) and powerful jets, usualy with a FRII morphology. But the energy budget is thought to be dominated by radiation driven winds.

In contrast to the radiative-mode AGN, *jet*-mode AGN, or maintenance-mode AGN (see Bicknell *et al.*, these proceedings), are generally characterized by low accretion efficiencies and are common at the present epoch when SMBHs are typically accreting well below the Eddington limit. Galaxies with such AGN are also known as low-excitation radio galaxies (LERGs; Hine & Longair 1979), and the radio sources responsible for the jet-mode feedback are lower-power sources with FRI morphology. The LERGs are thought to be powered by hot-mode accretion (for a review see Yuan & Narayan 2014), when the material falls directly onto the SMBH through accretion of cold clumps of gas (known as the *cold feedback mechanism*, Pizzolato & Soker 2005, 2010; Gaspari *et al.* 2012b; McCourt *et al.* 2012) with no accretion disc to ionize (see also observational support from Cavagnolo *et al.* 2011; Farage *et al.* 2012; McNamara *et al.* 2014), or directly from the hot atmosphere through Bondi accretion (Allen *et al.* 2006; Rafferty *et al.* 2008). Furthermore, the cold clumps in the cold feedback scenario might be responsible for re-starting the AGN activity (Morganti *et al.* 2009; Maccagni *et al.* 2014).

Jet-Mode AGN Feedback.Observational support for jet-mode AGN as a source of heating was highlighted soon after the launch of the *Chandra* X-ray Observatory, which found evidence that the lobes of the central AGN were inflating cavities in the X-ray atmospheres of many nearby clusters, groups and ellipticals. The cavities are a direct evidence of a strong coupling between the AGN and the ICM. Notable examples of cavities in the intracluster medium (ICM) of galaxy clusters include Perseus (Fabian *et al.* 2000), Hydra A (McNamara *et al.* 2000), A2052 (Blanton *et al.* 2001), MS 0735.6+7421 (McNamara *et al.* 2005, see Figure 1, *left*,), among many others (see Bîrzan *et al.* 2004; Dunn & Fabian 2004; Dunn *et al.* 2005; Rafferty *et al.* 2006). These cavities provide a straightforward means of estimating the energy being deposited by the AGN in the ICM (see Figure 1 *right*, Bîrzan *et al.* 2004), revealing that this mechanical power, if dissipated and turned into heat, is often more than enough to balance cooling (Rafferty *et al.* 2006).

The mechanical power is thought to be dissipated as the cavities lift up cold gas from the bottom of the potential well (Churazov *et al.* 2001; Revaz *et al.* 2008; Werner *et al.* 2010) and eventually break up. Additionally, the outbursts create weak shocks (Wise *et al.* 2007), with energies comparable to the cavity enthalpies (Brüggen *et al.* 2007); sound waves (Fabian *et al.* 2006); and heat through cosmic rays (CRs) injected at the tips of the jets (Böhringer & Morfill 1988; Loewenstein *et al.* 1991; Enßlin *et al.* 1997; Guo & Oh 2008; Enßlin *et al.* 2011; Wiener *et al.* 2013; Pfrommer 2013), all of which produce a convective core and provide heating isotropically (Tabor & Binney 1993; Chandran & Rasera 2007; Sharma *et al.* 2009). AGN heating can also come from radiative-mode AGN such as quasars (Ciotti & Ostriker 1997, 2001) or through primordial CRs from blazars (Pfrommer *et al.* 2012).

Additionally, besides jet-mode AGN heating, there are also non-AGN heating mechanisms, e.g. conduction (Zakamska & Narayan 2003; Voigt & Fabian 2004), turbulent mixing (Kim & Narayan 2003), mergers (Gómez *et al.* 2002), sloshing (ZuHone *et al.* 2010), SN (Domainko *et al.* 2004), turbulence energy triggered by SF and SN (Falceta-Gonçalves *et al.* 2010; de Gouveia Dal Pino *et al.* 2011), and gravitational heating from clumpy accretion (Dekel & Birnboim 2008).

However, while there is generally a consensus that the AGN at the cores of massive galaxies play an important role in regulating cooling in these systems, and recent X-ray and radio observations allowed us to quantify the energy budget of the AGN feedback process (Bîrzan *et al.* 2004, 2008), many details of the cycle of jet-mode heating and cooling are still poorly understood. For example, it is still unclear by which mechanism the AGN heats the cluster core (e.g., shocks, turbulence, or bubbles; Banerjee & Sharma 2014); what is the importance of turbulence, convection, cold-clumps and cosmic rays to AGN heating (Wagh *et al.* 2014; Hillel & Soker 2014; Gaspari *et al.* 2014); and how the gas cools onto the SMBH (Li & Bryan 2014).

2. The CF/NCF separation, complete samples, and the duty cycle of jet-mode AGN feedback

It is well established that the heat delivered by the radio source into the ICM is a critical part of the feedback process (McNamara & Nulsen 2007), but cooling is equally important and even less understood. Heating is expecting to occur only in systems where significant (residual) cooling is occurring (Rafferty *et al.* 2008; O'Dea *et al.* 2008; McDonald *et al.* 2011). As a result, it is important to select samples of systems that require heating in order to study jet-mode AGN feedback (Bîrzan *et al.* 2012). Also, cooling flow and non-cooling flow systems are intrinsically different, not only in their X-ray morphology, but also in their star formation rates, Hα luminosities, central source radio powers,

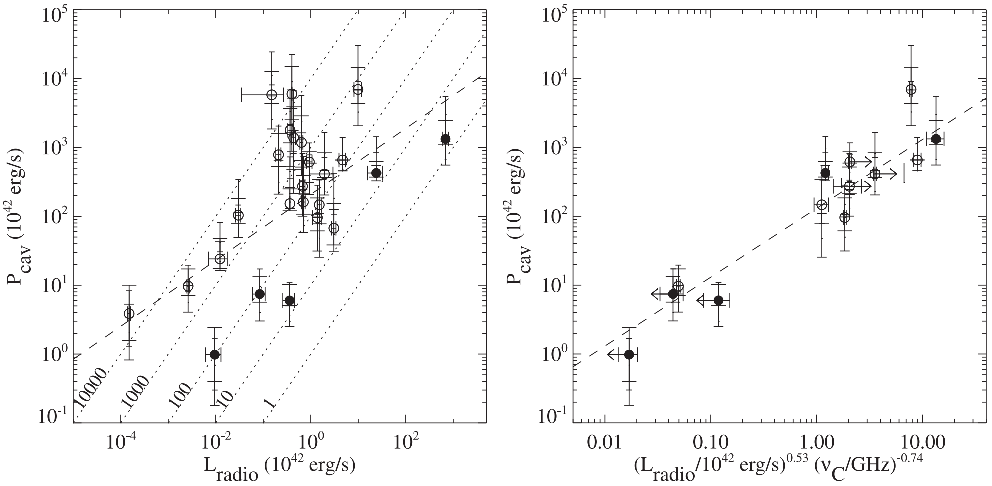

Figure 2. *Left*: Cavity power vs. bolometric radio luminosity (Bîrzan *et al.* 2008). *Right*: The scaling relation with the break frequency information included (on the x axis). The dash lines show the best-fit power law for the entire sample.

X-ray-to-optical centroid separations, etc. (e.g., Rafferty *et al.* 2008; Cavagnolo *et al.* 2008; Sun 2009; Bîrzan *et al.* 2012).

There are a number of different ways to separate cooling flows and non-cooling flows. For example, separations can be made using a temperature gradient criterion (Sanders & Fabian 2006), the concentration parameter (Santos *et al.* 2008; McDonald *et al.* 2013), or the central cooling time or entropy (O'Hara *et al.* 2006; Chen *et al.* 2007; Pratt *et al.* 2009; Cavagnolo *et al.* 2009; Hudson *et al.* 2010; McDonald *et al.* 2013). For the latter criteria, the choice of cooling-time or entropy threshold and radius can give different results (for a review see Sun 2012). The use of the central cooling time or entropy is supported by theoretical work (Voit *et al.* 2008; Voit 2011; McCourt *et al.* 2012; Sharma *et al.* 2012) that showed that there is a minimum thermal instability of the gas (or a minimum ratio between the cooling time of the gas versus the free-fall time) below which star-formation and Hα emission (and hence cooling) seem to occur (for more discussion see also Wagh *et al.* 2014).

In Bîrzan *et al.* (2012), we used both the inner cooling time criterion (Rafferty *et al.* 2008) and the minimum instability criterion (Voit *et al.* 2008), and we found that both criteria give similar results. Additionally we found that there is a smooth transition between cooling flows and non-cooling flows, with significantly more cooling flow systems, and we interpret the intermediate systems ($5 \times 10^8 < t_{\rm cool} < 10^9$ yr) as cooling flows without the need of heating through cavities (Bîrzan *et al.* 2012). Recently, similar results were found by Panagoulia *et al.* (2014a), who did not find evidence for bi-modality in central entropies (Cavagnolo *et al.* 2009). Generally, when using the central cooling time or entropy, it is important to sample these quantities as closely to the core as possible, through, e.g., the use of the X-ray surface brightness profile to trace density to smaller radii than possible with spectral fitting (Rafferty *et al.* 2008; Sanders *et al.* 2010).

By using complete samples of nearby cooling-flow systems we determined that the duty cycle of jet-mode feedback (the fraction of time that a system possesses cavities inflated by its central radio source) is at least $\approx 65\%$, and can be as high as 100%, if one accounts for the detectability of such cavities (Bîrzan *et al.* 2012). Similar results were found by Panagoulia *et al.* (2014b), using volume limited sample (see also Dunn *et al.*

2006; Fabian 2012). Furthermore, Panagoulia *et al.* (2014b) noticed possible evidence of continuous "bubbling-mode" feedback for the lower mass systems, in agreement with gentle self-regulated feedback models (Gaspari *et al.* 2011, 2012a). It is important to extend these studies to higher-redshift systems as well, and there is already plenty of *Chandra* data (e.g., on the SPT cluster sample; Bîrzan *et al.* in preparation) and new spectral deprojection methods that have been developed to deal with the low numbers of counts available in observations of such systems (Sanders *et al.* 2014).

3. Scaling relations between radio power and jet power

With present X-ray instruments, such as *Chandra*, the direct measurement of feedback power through X-ray observations is possible only for the most luminous systems where the cavities can be directly imaged. Therefore, many of the details of AGN feedback at higher redshifts, which are critical inputs to realistic models of galaxy formation and evolution, are poorly understood or constrained. To address this problem, much of my research has focused on studying the relation between jet power and radio luminosity in nearby systems with visible cavities in the X-ray images (see Figure 2, Bîrzan *et al.* 2004, 2008), with the goal of developing relations with which the jet power can be inferred from the radio power alone (see also Cavagnolo *et al.* 2010; Merloni & Heinz 2007; O'Sullivan *et al.* 2011; Daly *et al.* 2012; Godfrey & Shabala 2013).

However, the scatter in such relations is generally large. This scatter can be reduced by accounting for spectral aging (see Figure 2, *right*, Bîrzan *et al.* 2008). Additionally, these relations can be further improved with LOFAR data, as in many cases the current data are at frequencies that are too high to properly constrain the break frequency (i.e., the upper limits in Figure 2, *right*). LOFAR, with its sensitivity to very low frequencies (down to 10 MHz) and multifrequency coverage, will enable us to put better constraints on the energetically dominant low-frequency-emitting electrons, to better constrain the break frequencies and spectral ages, and to better understand the cavity and lobe contents. Furthermore, using very sensitive radio observations from LOFAR (i.e., deep wide-area surveys at low frequencies), one can probe the low luminosity AGN (LLAGN) in cluster and group environments and better understand jet-mode AGN feedback at high redshifts.

4. AGN feedback at high redshift, LOFAR prospects

The question of how much heating AGN produce at higher redshifts is important since it is at these redshifts that the bulk of galaxy and cluster formation occurred and, consequently, it is there that the effects of AGN feedback are most instrumental in shaping these processes. However, the only systematic study of jet-mode feedback in higher-redshift systems (out to $z \sim 0.5$) was done by Hlavacek-Larrondo *et al.* (2012) using the the MAssive Cluster Survey (MACS) sample and, as a result, is likely biased towards the most luminous cooling flow clusters. Instead, most studies of AGN feedback at high redshift (Lehmer *et al.* 2007; Smolčić *et al.* 2009; Danielson *et al.* 2012; Ma *et al.* 2013) rely on indirect methods of inferring AGN feedback powers, such as scaling relations between the jet power and the radio luminosity (e.g., Bîrzan *et al.* 2008). These studies generally do not find any evidence for evolution in the feedback properties, suggesting that the jet-mode feedback starts to operate as early as 7 Gyr years after the Big Bang ($z \sim 1.3$) and has not changed since then (see also Simpson *et al.* 2013), thus maintaining the same approximate balance between AGN heating and radiative cooling as in the local universe (Best *et al.* 2006). However, it is not well understood whether a locally derived

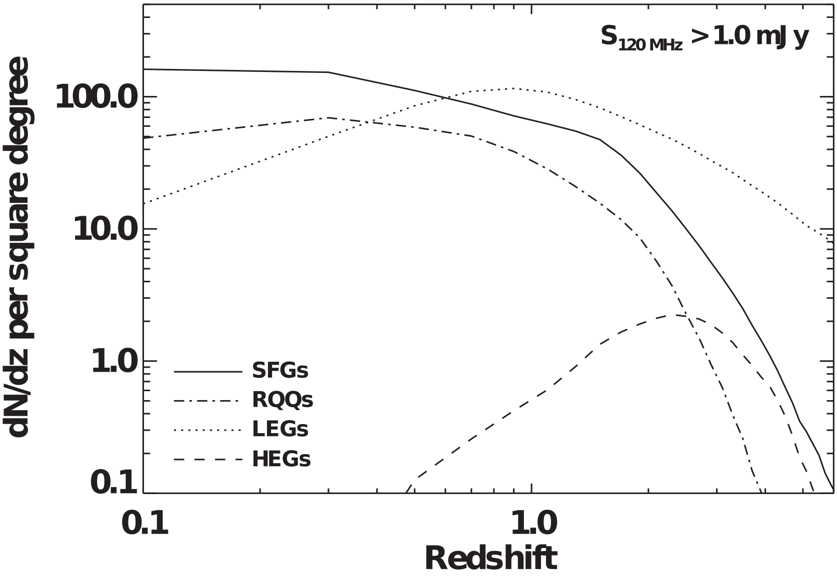

Figure 3. The number of sources predicted per square degree per redshift bin in the LOFAR HBA observations, to a 1 mJy limit (figure adapted by P. Best from Wilman *et al.* 2008). The sources are split into starforming galaxies (SFGs) and the AGN populations: RQ QSOs and RL AGN (LERGs, HERGs).

scaling relation applies at higher redshifts, especially given the evolution of the general population of AGN (LERGs vs. HERGs; see Figure 3).

Since the radio sources at the center of the clusters are usually LLAGN, which are now recognized to all be radio loud (Falcke *et al.* 2000; Ho 2002), very sensitive observations are required to study them. LOFAR deep-field surveys (of, e.g., the COSMOS, XMM/LSS, and NEP fields), together in the near future with eROSITA surveys, are perfectly suited for this task. LOFAR has the advantage of being a low-frequency telescope, and therefore more sensitive to steep-spectrum and high-redshift systems, and has a larger field of view suitable for surveys. As the simulations from Wilman *et al.* (2008) show (see Figure 3), above a flux of 1 mJy at 120 MHz LOFAR can detect hundreds of systems per square degree at $z \sim 1$ and tens at $z \sim 5$. The challenge will be to separate the RL AGN (LERGs and HERGs) from SFGs and RQ AGN (Padovani *et al.* 2011; Bonzini *et al.* 2013), both of which might be related with SF processes (Padovani *et al.* 2011) and not important for AGN feedback studies. Additionally, although radio-loud HERGs are often located in cluster environments at high redshift (Crawford & Fabian 1996; Worrall *et al.* 2001; Siemiginowska *et al.* 2010; Russell *et al.* 2012), their importance to jet-mode AGN feedback is not clear, since the radiative mode is expected to be the dominate feedback mechanism in these sources.

These issues aside, many of the tools necessary to perform such studies are now available. Recently, it has been demonstrated that LOFAR can produce thermal-noise-limited images, with a noise of 100 μJy/beam for 9 hours of integration (van Weeren *et al.* 2014, in preparation). For a typical source spectral index of $\alpha = 1$, this 140 MHz LOFAR image has a similar noise to very deep VLA 1.4 GHz images, e.g., those of the CDFS (≈ 10 μJy/beam; Bonzini *et al.* 2013). However, the LOFAR image is ~ 5 times more sensitive than such VLA images to sources with an $\alpha = 1.5$ at $z = 1$. Therefore, LOFAR looks set to fulfill its potential as one of the most important instruments for the study of high-redshift jet-mode AGN feedback.

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