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OUTFLOWS, BUBBLES, AND THE ROLE OF THE RADIO JET: DIRECT EVIDENCE FOR AGN FEEDBACK AT Z∼2

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Abstract. To accommodate the seemingly "anti-hierarchical" properties of galaxies near the upper end of the mass function within our hierarchical paradigm, current models of galaxy evolution postulate a phase of vigorous AGN feedback at high redshift, which effectively terminates star formation by quenching the supply of cold gas. Using the SINFONI IFU on the VLT, we identified kpc-sized outflows of ionized gas in z∼2−3 radio galaxies, which have the expected signatures of being powerful AGN-driven winds with the potential of terminating star formation in the massive host galaxies. The bipolar outflows contain up to few$\times 10^{10}$ M$_{\odot}$ in ionized gas with velocities near the escape velocity of a massive galaxy. Kinetic energies are equivalent to $\sim 0.2\%$ of the rest mass of the supermassive black hole. We discuss the results of this on-going study and the global impact of the observed outflows.

1 The role of AGN feedback for galaxy evolution in the early universe

AGN feedback is now a critical element of state-of-the-art models of galaxy evolution tailored to solve some of the outstanding issues at the upper end of the galaxy mass function. Observationally, a picture emerges where AGN feedback is most likely related to the mechanical energy output of the synchrotron emitting, relativistic plasma ejected during the radio-loud phases of AGN activity: Giant cavities in the hot, X-ray emitting halos of massive galaxy clusters filled with radio plasma are robust evidence for AGN feedback heating the gas on scales of massive galaxy clusters (e.g., McNamara & Nulsen, 2007). Best et al. (2006) analyzed a large sample of early-type galaxies from the SDSS catalog with FIRST and NVSS radio data and found that heating by the radio source may well balance gas cooling over 2 orders of magnitude in radio power and in stellar mass.

However, since most of the growth of massive galaxies was completed during the first few Gyrs after the Big Bang, observations at low redshift can only provide evidence that AGN feedback is able to *maintain* the hot, hydrostatic halos of massive early-type galaxies (*"maintenance mode"*). If we want to observe directly whether AGN feedback indeed quenched star formation and terminated galaxy growth in the early universe (*"quenching mode"*), we have to search at high redshift. With this goal, we started a detailed analysis of the rest-frame optical line emission in powerful, z∼2−3 radio galaxies with integral field spectroscopy, where we may plausibly expect the strongest signatures of AGN-driven winds.

2 Powerful radio galaxies at z∼ 2−3: Dying starbursts in the most massive galaxies?

The observed properties of HzRGs suggest they may be ideal candidates to search for strong, AGN-driven winds: They have large stellar (Seymour et al. 2007) and dynamical (Nesvadba et al. 2007a) masses of $\sim 10^{11-12}$ M$_{\odot}$ and reside in significant overdensities of galaxies suggesting particularly massive underlying dark-matter halos (e.g., Venemans et al. 2007). Large molecular gas masses in some sources (e.g., Papadopoulos et al. 2000) and submillimeter observations suggest that some HzRGs at redshifts $z \geq 3-4$ are dust-enshrouded, strongly star-forming galaxies with FIR luminosities in the ULIRG regime. Interestingly, the fraction of submillimeter-bright HzRGs shows a rapid decline from >50% at z>2.5 to ≤15% at z<2.5 (Reuland et al. 2004). This suggests that HzRGs may be particularly massive galaxies near the end of their phase of active star formation. They also host particularly powerful AGN. Thus, they are good candidates to search for the kinematic signatures of AGN-driven winds.

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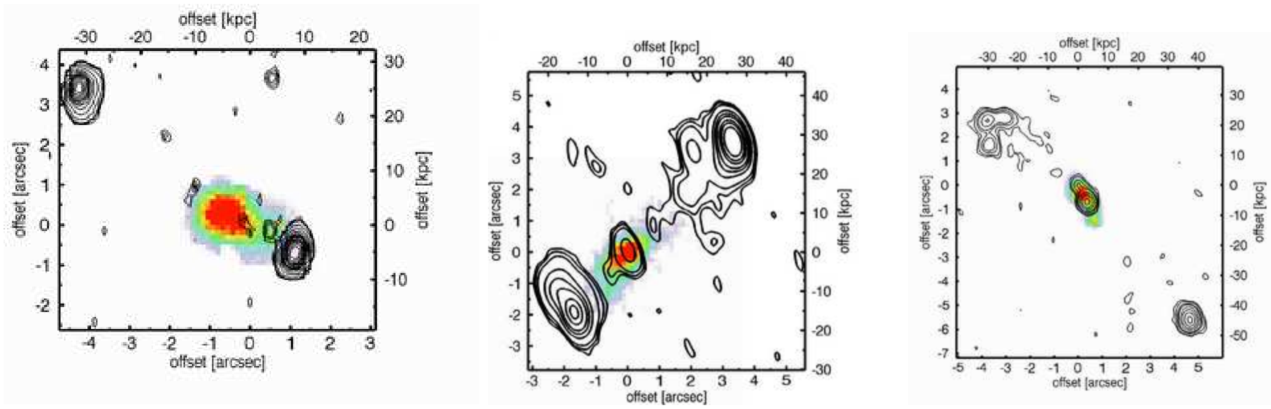

Fig. 1. *(left to right:)* [OIII]λ5007 emission line morphologies of MRC0316-257 at z=3.1, MRC0406-244 at z=2.4 and TXS0828+193 at z=2.6. Contours indicate the line-free continuum morphology for MRC0406-244 and TXS0828+193, and the 4.8 GHz radio core for MRC0316-257, where we did not detect the continuum.

3 Observational evidence for AGN-driven winds in z$\sim$2$-$3 radio galaxies

To directly investigate whether HzRGs may be the sites of powerful, AGN driven winds, we collected a sample of HzRGs at redshifts z$\sim$2$-$3 with rest-frame optical near-infrared spectral imaging obtained with SINFONI on the VLT. Including scheduled observations, our total sample will consist of 29 galaxies spanning wide ranges in radio power and radio size. We also include galaxies with compact, and probably young, radio sources. We will in the following concentrate on the analysis of a first subsample of 6 galaxies, 4 with extended jets with radii between 10 and 50 kpc, 2 with more compact radio sources <10 kpc in radius. For details see Nesvadba et al. (2006, 2007a, 2008).

3.1 Continuum and emission line morphologies

Using an integral-field spectrograph, we were able to extract continuum-free line images as well as line-free continuum images from our three-dimensional data cubes (Fig. 1). We find that in all cases, the continuum emission is relatively compact, but spatially resolved in some cases, with half-light radii $\leq$ 5 kpc. Radio-loud AGN activity is often related to an on-going merger. However, we only identify one continuum knot per galaxy. For the merger scenario, this may suggest an advanced stage where the galaxies are seperated by less than the $\sim$ 4 kpc spatial resolution of our data. Alternatively, since SINFONI is relatively inefficient in detecting low surface-brightness continuum emission, nuclear activity may have been triggered by other processes like minor mergers or perhaps cooling flows in cluster environments.

The extended, distorted morphologies of HzRGs with extended jets seen in broad-band imaging are mostly due line contamination, originating from emission line regions that extend over several 10s of kpc, and are significantly larger than the continuum (Nesvadba et al. 2008), but extend to smaller radial distances than the radio lobes. The same is found from Lyα longslit spectroscopy (e.g., Villar-Martin 2003). Overall, different emission lines in the same galaxy show similar morphologies. In the galaxies with *compact* radio sources, the line emission appears also compact. This may suggest a causal relationship between the advance of the jet and the extent of the high surface brightness emission line gas.

3.2 Kinematics, outflow energies, and physical properties of the ionized gas

We fitted spectra extracted from individual spatial resolution elements to construct two-dimensional maps of the relative velocities and line widths (Fig. 2). Typically, the velocity maps show two bubbles with relatively homogeneous internal velocity, and projected velocities relative to each other of 700$-$1000 km s^{-1}, reminiscent of back-to-back outflows extending from near the radio core. MRC1138-262 has a more complex structure with at least 3 bubbles. Line widths are generally large, indicating strong turbulence, with typical FWHMs $\sim$500$-$1200 km s^{-1}. Areas with wider lines may be due to partial overlap between bubbles.

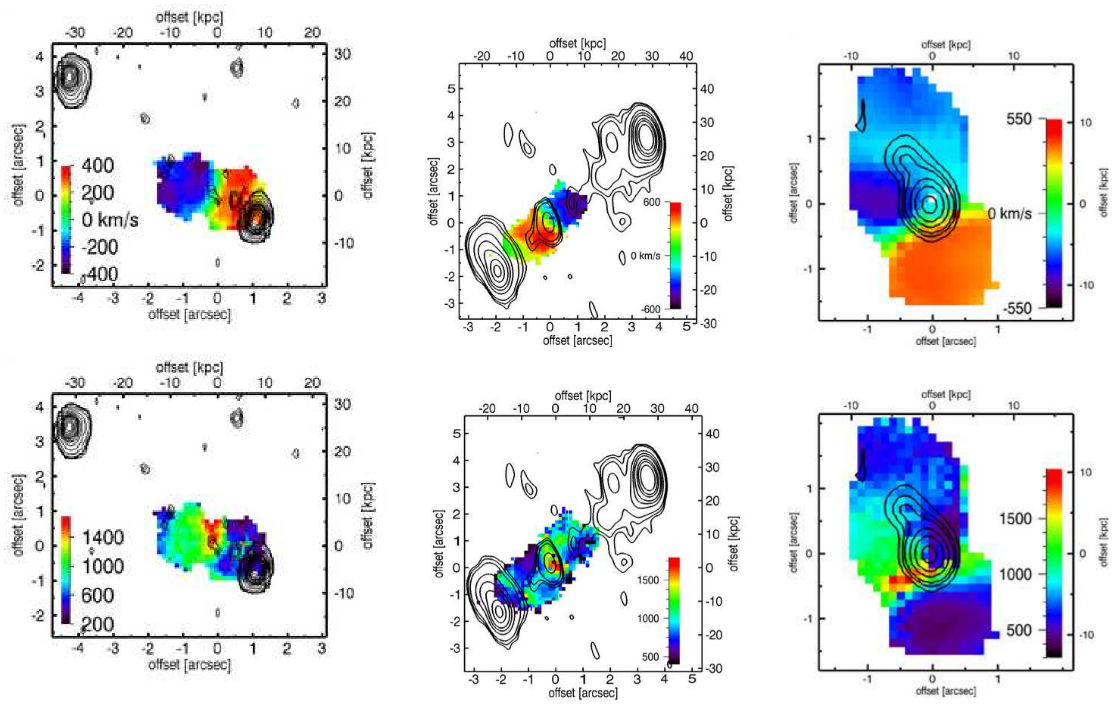

Fig. 2. *top, left to right:* Maps of relative velocities (in km s^{-1}) for MRC0316-257 at z=3.1, MRC0406-244 at z=2.4, and TXS0828+193 at z=2.6. *bottom, left to right*: Maps of FWHMs (in km s^{-1}) for the same galaxies. Contours show the jet morphologies. For TXS0828+193, the lobes are outside of the area shown.

Filamentary morphologies and low gas filling factors suggest that the UV-optical line emission may originate from clouds of cold gas that are being swept up by an expanding hot medium, most likely related to the overpressurized 'cocoon' of gas heated by the radio jet. In such a scenario the velocity of the clouds may yield an estimate of the kinetic energy injection rate necessary to accelerate the gas to the observed velocities of up to $\sim 10^{45}$ erg s^{-1} (Nesvadba et al. 2006). The size and velocities of the outflow suggest dynamical timescales of few $\times 10^7$ yrs. Maintaining the observed outflows over such timescales requires total energy injections of $\sim 10^{60}$ erg. This is in the range of what is observed for AGN driven bubbles in massive clusters at low redshift (e.g., McNamara & Nulsen, 2006, and references therein). The observed velocities and kinetic energies are also in the range of escape velocities and binding energies expected for galaxies with masses of few $\times 10^{11}$ $M_\odot$ (Nesvadba et al. 2006). This may suggest that much of the gas participating in the outflows may ultimately be unbound from the underlying gravitational potential.

3.3 Molecular and ionized gas budgets

Having measured Hα line fluxes, we are able to roughly estimate ionized gas masses assuming case B recombination (see Nesvadba et al. 2008 for details). For galaxies where we also measured Hβ, we correct for extinction of $A_V \sim 1-4$ mag and find ionized gas masses of up to few $\times$ 10^{10} $M_\odot$. (Without the correction, estimates are few $\times 10^9$ $M_\odot$, Nesvadba et al. 2008.) This exceeds the amount of ionized gas found in any other high-redshift galaxy population by several orders of magnitudes, including galaxies with starburst-driven winds. Nesvadba et al. (2007b) investigated a spatially-resolved, starburst driven wind in a strongly star-forming submillimeter-selected galaxy at z$\sim$2.6 with of order few$\times 10^6$ $M_\odot$ in ionized gas in the wind. Compact radio galaxies have lower entrained gas masses, but in the range of what would be expected for less evolved outflows with similar entrainment rates as the galaxies with large radio lobes (Nesvadba et al. 2007a).

Molecular gas masses in strongly star-forming galaxies at high redshift are also typically in the range of few $\times 10^{10}$ $M_\odot$ (e.g., Neri et al. 2003), and are a necessary prerequisite to fuel the observed starbursts with star formation rates of few 100 $M_\odot$ yr^{-1}. However, not all HzRGs have been detected in CO. TXS0828+193 specifically, which is part of our sample, appears to have less than $\sim 10^{10}$ $M_\odot$ in molecular gas (Nesvadba et al., in prep.). This illustrates that the AGN winds may affect a significant fraction of the overall interstellar medium of strongly star-forming, massive galaxies in the early universe. Since the velocities are near the expected escape velocity of a massive galaxy and underlying dark-matter halo (§3.2), much of this gas may actually escape.

4 Global impact of AGN driven winds

Four out of four HzRGs with extended radio jets show evidence for outflows with with kinetic energies of up to 10^{60} erg over dynamical timescales of 10^7 yrs, and the preliminary analysis of our full sample suggests that this is far from being unusual. Nesvadba et al. (2006, 2008) estimate that the outflow energies correspond to $\sim 10\%$ of the jet kinetic luminosity. If this coupling efficiency between jet and interstellar medium is typical for HzRGs with similarly powerful radio sources, then the redshift-dependent luminosity function of Willott et al. (2001) suggests that at redshifts z$\sim 1-3$, AGN-winds release an overall energy density of about 10^{57} erg s^{-1} Mpc^{-3}. Some of this energy release may contribute to heating and increasing the entropy in extra-galactic gas surrounding the HzRG, and to enhance gas stripping in satellite galaxies, so that subsequent merging with satellites will be relatively dissipationless. This may later contribute to preserving the low content in cold gas and old, luminosity weighted ages of the highly metal-enriched stellar population in massive galaxies to the present day, in spite of possible continuous accretion of satellite galaxies over cosmologically significant periods (Nesvadba et al. 2008).

If the outflows are related to the nuclear activity, then the ultimate energy source powering the outflow is accretion onto the supermassive black hole in the center of the galaxy. Thus, models of galaxy evolution often parameterize the efficency of AGN feedback by the energy equivalent of the rest mass of the black hole. Since we have reason to believe that HzRGs approximately fall onto the low-redshift M-σ relationship between the mass of the supermassive black hole and velocity dispersion of the host, we can use the stellar mass estimates of Seymour et al. (2007) to roughly estimate the black hole mass of our targets. We find that of order 0.1% of the energy equivalent of the black hole mass in HzRGs is being released in kinetic energy of the outflows. A similar estimate based on the global energy density released by powerful radio galaxies estimated above, and the local black hole mass density yields a very similar result, $\sim 0.2\%$. This is very close to what is assumed in galaxy evolution models (e.g., Di Matteo et al. 2005), and highlights the likely importance of the observed outflows on galaxy evolution.

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