

Blowin' in the wind: both 'negative' and 'positive' feedback in an outflowing quasar at $z \sim 1.6$

Giovanni Cresci

INAF - Osservatorio Astrofisico di Arcetri, largo E. Fermi 5, 50127, Firenze, Italy
email: gcresci@arcetri.astro.it

Abstract. Quasar feedback in the form of powerful outflows is invoked as a key mechanism to quench star formation, preventing massive galaxies to over-grow and producing the red colors of ellipticals. On the other hand, some models are also requiring 'positive' AGN feedback, inducing star formation in the host galaxy through enhanced gas pressure in the interstellar medium. However, finding observational evidence of the effects of both types of feedback is still one of the main challenges of extragalactic astronomy, as few observations of energetic and extended radiatively-driven winds are available. We present SINFONI near infrared integral field spectroscopy of XID2028, an obscured, radio-quiet $z = 1.59$ QSO, in which we clearly resolve a fast (1500 km/s) and extended (up to 13 kpc from the black hole) outflow in the [OIII] lines emitting gas, whose large velocity and outflow rate are not sustainable by star formation only. The narrow component of H α emission and the rest frame U band flux show that the outflow position lies in the center of an empty cavity surrounded by star forming regions on its edge. The outflow is therefore removing the gas from the host galaxy ('negative feedback'), but also triggering star formation by outflow induced pressure at the edges ('positive feedback'). XID2028 represents the first example of a host galaxy showing both types of feedback simultaneously at work.

Keywords. Galaxies: active - Galaxies: evolution - ISM: jets and outflows

1. Introduction

We have recently completed two follow-up programs on obscured quasars pre-selected for being in a significant outflowing phase. The first consists in X-Shooter observations of a sample of X-ray selected obscured QSOs at $z \sim 1.5$, selected from the XMM-COSMOS survey on the basis of their observed red colors ($R-K > 4.5$) and high MIR and X-ray to optical flux ratio ($X/O > 10$, see Brusa *et al.* 2010). The presence of outflowing material identified by [OIII] $\lambda 4958,5007$ kinematics was indeed detected in 6 out of 8 sources, confirming the efficiency of a selection based on X-ray to optical to NIR colors in isolating such objects undergoing a 'blow-out' phase (Brusa *et al.* 2014).

We also recently completed a SINFONI program on a sample of AGN pre-selected to have high accretion rates, where radiatively-driven winds are supposed to be more effective since they likely originate from the acceleration of disk outflows by the AGN radiation field, and a combination of moderate obscuration observed in the X-rays and high Eddington ratio where outflows or transient absorption are expected to happen (Fabian *et al.* 2008). Interestingly, XID2028 at $z = 1.59$ was selected as an obscured, outflowing QSOs using both criteria described above.

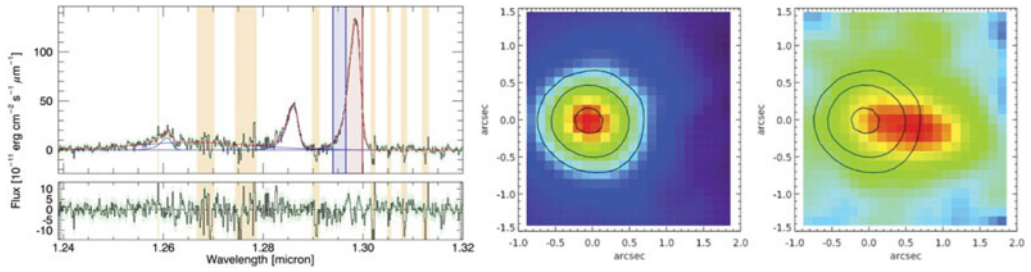


Figure 1. [OIII] in XID2028. *Left panels:* the J band SINFONI spectrum of XID2028, integrated in a region of 8×8 spaxels ($1'' \times 1''$) around the QSO. The observed spectrum is shown in black, the different broken power-law components in the fit for each line ($H\beta$, large BLR $H\beta$, $[OIII]\lambda 4959, 5007$) are shown in blue, while their sum is shown in red. The shaded regions show the location of sky lines, that were excluded from the fit. The red and blue box show the intervals in wavelength in which the maps shown in the right panels are integrated. *Right Panels:* $[OIII]\lambda 5007$ channel maps obtained integrating the continuum subtracted SINFONI datacube on the line core (*left*, red box) and on the blue wing (*right*, blue box). The contours on the line core, marking the position of the central QSO, are shown in black in both panels. The fully resolved, extended blue wing due to the outflow is extended up to $1.5''$, i.e. 13 projected kpc from the QSO position. North is up and East is left, $1''$ corresponds to 8.5 kpc.

2. Results

The integrated J band SINFONI spectrum of XID2028 is shown in Fig. 1: an asymmetric, prominent blue wing is clearly visible for all the emission lines, already suggesting the presence of outflowing material towards the observer. In fact, the forbidden [OIII] emission lines are an ideal tracer of extended outflowing ionized gas, as cannot be produced in the high-density, sub-parsec scales typical of AGN broad-line regions (BLR). To assess the spatial extent of the blueshifted wing, in Fig. 1 we also show the continuum subtracted SINFONI datacube collapsed on the spectral channels corresponding to the line core and to the line wing. The prominence of an extended, fully resolved outflow is evident from the image of the blue wing in the west-east direction. The blue wing is originating on the QSO position, as marked from the line core black contours, and it is extending up to $1.5''$, i.e. 13 projected kpc, from the center.

We have fitted separately the spectrum of each spatial spaxel in the field of view using a broken power law, in order to measure and map the velocity of the [OIII] line wing. We measure strongly blueshifted velocities in the outflow region, with velocities as high as $v_{10} = -1500 \text{ km/s}$ towards our line of sight, where v_{10} is the velocity at the 10th percentile of the overall emission-line profile. The detected velocity are far too high to be due to rotational motions in the host galaxy. Moreover, in case of ordered rotation we expect the line width to be peaked at the center of the galaxy (e.g. Cresci *et al.* 2009), while in this case the line width is larger in the blue wing region.

We used the $H\beta$ emission in the outflow region to derive an estimate of the ionized outflowing mass. Depending on a number of assumptions (see Cresci *et al.* 2014), we estimate a mass outflow rate $\dot{M}_{out} \sim 300 M_{\odot}/\text{yr}$ for the ionized component only, which may correspond to a total outflow rate of $\dot{M}_{out} \gtrsim 1000 M_{\odot}/\text{yr}$ when accounting for a neutral and molecular component. This would translate to a mass loading factor $\gtrsim 3$, suggesting that such an energetic outflow is not sustainable by star formation only.

We fitted the integrated H+K SINFONI spectrum in the $H\alpha$ region with a single broad Gaussian, finding a $FWHM = 3600 \text{ km/s}$. Although a single Gaussian represents a good fit on the wings of the emission line, a weaker but significant narrow component is present in the fit residuals. The redshift $z = 1.594$ of this narrow component ($FWHM =$

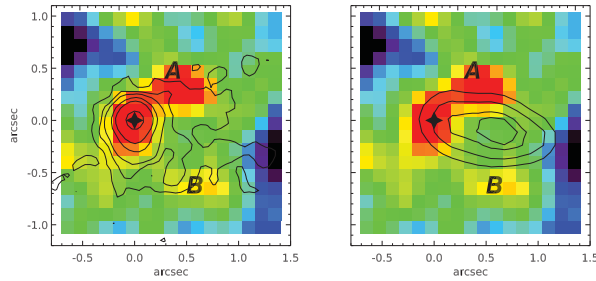


Figure 2. Narrow $H\alpha$ map obtained integrating the single broad Gaussian $H\alpha$ fit residuals on the spectral channels $1.7015 < \lambda < 1.7047 \mu\text{m}$. In the *left panel* the HST-ACS rest frame U band contours are superimposed in black. The same pattern is obtained by these two independent tracers of star formation in the host galaxy, with two additional clumps of star formation (marked with A and B) elongated at the west of the QSO (marked with a star). In the *right panel* the blue wing contours from Fig. 1, tracing the outflow position, are plotted for comparison. A clear anti-correlation between the outflow location and the star formation tracers suggests that the outflowing material is sweeping the gas along the outflow core (‘negative feedback’), while is compressing the gas at its edges inducing star formation at the locations marked as A and B on the map (‘positive feedback’).

320 km/s) is consistent with the systemic redshift of the host galaxy (Brusa *et al.* 2010), and it is interpreted as due to the star formation in the host galaxy.

We map the spatial extent of the $H\alpha$ narrow component by fitting in each spaxels of the datacube the single Gaussian derived from the integrated spectrum, keeping the width and centroid fixed and leaving the normalization free to vary. We then integrate on the spectral channels corresponding to the narrow component in the integrated spectrum ($1.7015 < \lambda < 1.7047 \mu\text{m}$) the residual map obtained subtracting the Gaussian fit to the datacube. The result is illustrated in Fig. 2, where we show that the star formation in the host is not symmetrical distributed: most of the star formation activity is concentrated in the nucleus and in just two additional clumps, elongated to the west away from the QSO in two almost parallel branches around the location of the outflow (marked as A and B, detected in an integrated spectrum at 9σ and 4σ respectively). We derive a limit of $\log([NII]/H\alpha) < -1.1$ over the regions A and B. The narrow components of $H\beta$ and $[OIII]\lambda 5007$ are undetected across all the field of view, making impossible to place the two regions on classical AGN-star forming galaxies BPT spectral diagnostic. Nonetheless, the limit derived for $[NII]/H\alpha$ is already supporting a star forming origin of the line emission, as no known AGN shows such low values of this ratio (Kauffmann *et al.* 2003). For comparison, we measure $\log([NII]/H\alpha) = -0.4$ for the narrow components in the nuclear region, fully consistent with AGN ionization.

The same peculiar spatial pattern is also found in the available HST-ACS F814W imaging, sampling the rest frame U band at the redshift of the source (Fig. 2, left panel). Although at least part of the U emission may be due to scattered light from the QSO, the U band is also sensitive to the light emitted by young, massive stars. Therefore, the similarity of the shape of the U-band image with that of the narrow $H\alpha$ emission suggests that the U continuum is also dominated by star formation that covers a horseshoe region around the outflow. Interestingly, the outflow position is coincident with the cavity between these two star forming regions (Fig. 2) both in the narrow $H\alpha$ residuals maps as well as in the ACS rest frame U image. The star formation activity is therefore heavily suppressed in the core of the outflow, where the fast expanding gas is able to sweep away the gas needed to sustain the assemble of new stars. This represents a clear example of ‘negative feedback’ in action, showing the powerful outflow expelling most of the gas and

quenching the star formation along its route in the host galaxy. On the other hand, we also find evidence that enhanced, triggered star forming activity is detected in the two off-center, elongated regions surrounding the bulk of the outflow, marked as *A* and *B* in Fig. 2. The causal connection between the outflows and the star forming regions is supported by the highly asymmetric shape of the star forming regions, that are extending out of the galaxy exactly along both edges of the outflow, while no other tail or star forming clump is detected in the rest of the host galaxy: the integrated flux of the narrow H α line emission in the rest of the disk is $\sim 40\%$ of regions A and B alone.

3. Conclusions

These observations suggest that we are also witnessing ‘*positive feedback*’ in the host galaxy with the gas clouds compressed by the outflow-driven shock, which drives turbulent compression especially at the outflow edges. Such ‘positive feedback’ has been invoked in recent years to explain the correlation between AGN luminosities and nuclear star formation rates as well as between black hole accretion rate and star formation rate in AGN (Ishibashi *et al.* 2012, 2014; Silk 2013, Zinn *et al.* 2013). Despite its possible importance, the few available observational evidences of such feedback were till now ascribed to an handful of extreme, powerful jets in radio-loud galaxies (Feain *et al.* 2007, Crockett *et al.* 2012). Moreover, the outflow-induced star formation has been usually found not in the AGN host galaxy, but in a companion satellite aligned along the radio axis (Croft *et al.* 2006, Elbaz *et al.* 2009, Kramer *et al.* 2004).

Therefore, XID2028 represents the first direct detection of outflow induced star formation in a radio quiet AGN, as well as the first example of both types of feedback simultaneously at work in the same galaxy. As the quasar is observed at the peak epoch of galaxy and black hole assembly, where we expect to have the maximum influence of feedback on galaxy evolution, the data presented demonstrate that both ‘positive’ and ‘negative’ AGN feedback are a crucial ingredient to shape the evolution of galaxies, by regulating the star formation in the host and driving the BH-galaxy coevolution.

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