The KMOS AGN Survey at High Redshift (KASHz)

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The KMOS AGN Survey at High Redshift (KASHz) is an extensive observational programme to obtain spatially resolved spectroscopy of distant galaxies that host rapidly growing supermassive black holes (i.e., active galactic nuclei [AGN]). By exploiting the unique capabilities of KMOS we will spatially resolve the ionised gas kinematics in around 200 such galaxies. A fundamental prediction of galaxy formation models is that AGN inject considerable energy into their host galaxies and ultimately destroy or remove star-forming material via outflows. However, until now, observational constraints of this prediction have been limited to only a small number of distant galaxies. KASHz will provide the strongest constraints to date on the prevalence, properties and impact of ionised outflows in the host galaxies of distant AGN. The survey is described and our first results presented.

Matching models with observations: AGN to the rescue

Over the last three decades, the growth of supermassive black holes (i.e., AGN) have moved to the forefront of galaxy evolution research. Historically, these energetic phenomena were considered rare, yet fascinating, objects to study in their own right. However, observations now indicate that all massive galaxies have hosted AGN activity during their lifetimes. Furthermore, the most successful models of galaxy evolution are unable to reproduce fundamental observations of local massive galaxies and galaxy clusters without implementing energetic feedback processes that couple AGN to the gas in their host galaxies, and beyond.

How can growing supermassive black holes be so critical in galaxy formation and evolution when they are a billion times more compact than the galaxies in which they reside in? Simply put, AGN are incredible energy sources. For example, accreting material to create a black hole like the one at the centre of the Milky Way (i.e., a mass equivalent to around $4 \times 10^6 M_\odot$) could liberate 7×10^{52} Joules of energy (equivalent to 10^{35} times the energy released by the most powerful nuclear weapons ever made). Theoretically, even if a small fraction of this energy is able to couple to the gas, all of the host galaxy's gas could become unbound. Inevitably at least some of gas is going to be heated and/or driven away in outflows. This material could otherwise have gone on to form stars and therefore the AGN has had a direct impact on the future evolution of its host galaxy.

Such effects are required in cosmological models of galaxy evolution to reproduce realistic populations of galaxies (e.g., Vogelsberger et al., 2014; Schaye et al., 2015); however, whilst theoretically attractive, observations are required to refine or refute these models. As we will describe in this article, our new large survey using the *K*-band Multi-Object Spectrograph (KMOS) mounted on the Very Large Telescope (VLT) will play a key role in providing observational constraints on the prevalence, properties and impact of outflows in the host galaxies of distant AGN.

Previous observations of AGN-driven outflows

For several decades it has been known that AGN drive gas away in fast outflows. Ultraviolet and X-ray spectroscopy have revealed that ultra-fast outflows in the proximity of accreting supermassive black holes are extremely common and may even be ubiquitous (e.g., Ganguly & Brotherton, 2008). However, of more direct relevance to the evolution of galaxies is the growing amount of observational evidence of outflows extending out to much larger scales, where they can have a direct impact on the star-forming material inside the host galaxies. This evidence mostly comes from spatially resolved spectroscopy, where emission or absorption lines can be used to trace the movements of the gas over these spatial scales. A variety of such observations of nearby and distant sources have revealed gas in molecular, atomic and ionised phases that appears to be being driven out of galaxies (e.g., Rupke & Veilleux, 2013; Harrison et al., 2014; Cicone et al., 2014). While these effects appear to be common across all galaxies with ongoing star formation, there is growing evidence, at least in the local Universe, that the most extreme outflows are associated with ongoing AGN activity (e.g., Cicone et al., 2014).

For our work, we are particularly interested in warm (~ 10^4 K) ionised outflows, which can easily be traced using restframe optical emission lines such as [O III] and Hα. An emission-line profile that is broad (from a few 100s to ≈ 1000 km s^{-1}) and/or asymmetric is strong evidence for outflowing material. Due to large optical spectroscopic surveys, such as the Sloan Digital Sky Survey (SDSS), which contains one-dimensional spectra of millions of galaxies, it is possible to search for such features in huge samples of nearby galaxies at late cosmic epochs (i.e., redshifts of $z \lesssim 0.4$; see Figure 1).

For example, Mullaney et al. (2013) constrained the prevalence of outflow features in the restframe optical emission lines for ≈ 24 000 AGN host galaxies exploiting the SDSS survey. Spatially resolved spectroscopy can then be performed using optical integral field units (IFUs) to measure key properties of subsets of

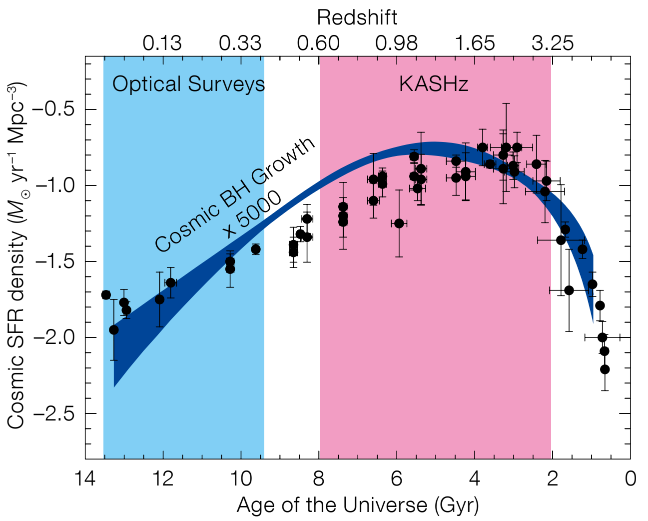

Figure 1. Volume-averaged star formation rate (SFR) density (circles; Madau & Dickenson, 2014) and scaled-up black-hole (BH) growth (curve; Aird et al., 2010) versus age of the Universe and redshift. The highlighted region shows the epochs covered by: (1) most optical spectroscopic surveys of warm ionised outflows (e.g., Mullaney et al., 2013); and (2) our new KASHz survey. Our first paper (Harrison et al., 2016) covers the peak epoch of BH and galaxy growth.

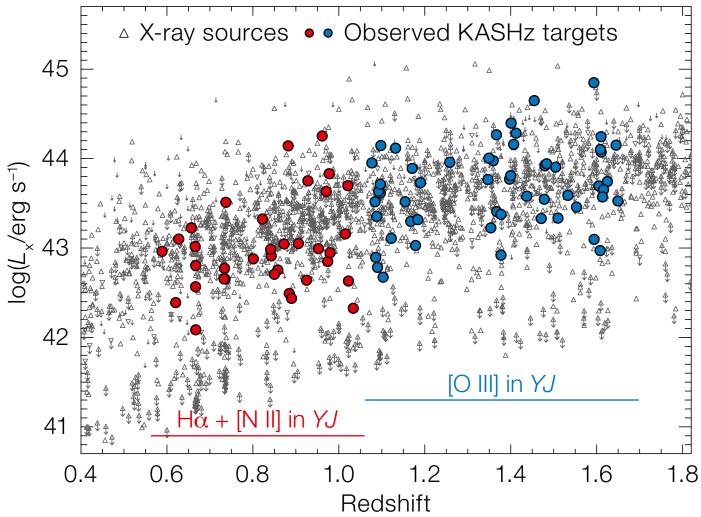

Figure 2. X-ray luminosity versus redshift for X-ray sources in the four deep fields covered by KASHz. The X-ray AGN with KMOS or SINFONI IFU data that appear in our first KASHz paper are highlighted with filled symbols.

these outflows, such as their spatial distribution and energetics (e.g., Harrison et al., 2014). Crucially, these IFU observations (and other multi-wavelength follow-up observations) can then be placed in the context of the parent population as a whole, making it possible to understand how representative these observations are and to compare them to cosmological simulations of galaxy evolution that predict such outflows.

The need for KMOS

As described above, a lot of work has been done using optical spectroscopy of low-redshift galaxies (i.e., at late cosmic epochs) to understand the prevalence and properties of galaxy-wide ionised outflows. However, much less work has been done at high redshift (i.e., early cosmic epochs; $z \approx 1$–3). This is largely due to the fact that the key restframe optical emission lines for the required analyses are shifted to near-infrared wavelengths for these distant galaxies. There has been some successful work on small numbers of objects using near-infrared IFUs, such as SINFONI on the VLT (e.g., Cano-Díaz et al., 2012; Cresci et al., 2015). However, until recently, it has been difficult to obtain large samples of near-infrared spectroscopy due to a lack of instrumentation. This has resulted in a significant deficit in our understanding of AGN feedback and outflows, because AGN activity and star formation are at their peak during early epochs ($z \approx 1$–3) and outflows may be most prevalent (see Figure 1).

Therefore, it has not been possible to constrain the prevalence and properties of ionised outflows in the high-redshift AGN and galaxy population as a whole. This is where KMOS comes to the rescue (Sharples et al., 2013). KMOS, which has been in operation at the VLT since November 2012, has 24 near-infrared IFUs that can be moved independently inside a 7-arcminute field of view. It is therefore ideally suited to rapidly build up large samples of high-redshift AGN host galaxies with high quality spatially resolved spectroscopy of the restframe optical emission lines (e.g., Bower & Bureau, 2014; Wisnioski et al., 2015). We have been exploiting the unique capabilities of KMOS to carry out such a survey — the KMOS AGN Survey at High Redshift (KASHz).

The KMOS AGN Survey at High Redshift

KASHz is designed to ultimately obtain spatially resolved emission-line kinematics of 100–200 high-redshift ($z \sim 0.6$–3.6) AGN. These data will primarily be obtained using KMOS guaranteed time observations, led by Durham University. This will be supplemented with archival data obtained using SINFONI, the single-object near-infrared IFU. The overall aim of KASHz is to provide insight into the feeding and feedback processes occurring in the host galaxies of high-redshift AGN by using IFU data to measure the ionised gas kinematics traced by the Hα, [O III], Hβ, [N II] and/or [S II] emission lines. The key aspect of KASHz is to exploit the unique capabilities of the multiple IFUs in the KMOS instrument to perform such measurements on larger, more uniformly selected samples of high-redshift AGN than was possible in previous studies that used single IFU instruments. This approach will make it possible to draw conclusions on the overall high-redshift AGN population and to place previous observations of a few sources in the context of the parent population of AGN. Until now, this sort of approach has only been possible for low-redshift AGN. Furthermore, our sample will provide an excellent characterisation of the parent population that can be used for efficient, multi-wavelength follow-up observations.

KASHz observations and first results

The first results from KASHz were published in Harrison et al. (2016). This study contains KMOS guaranteed time observational data from ESO Periods 92 to 95, as well as archival SINFONI data. This first study is of z = 0.6–1.7 AGN that were selected using X-ray wavelengths in the redshift range z ~ 0.6–1.7 (see Figure 2) and observed in the *YJ*-band. X-rays are excellent for identifying AGN because, for the most luminous emitters ($L_X > 10^{42}$ erg s^{-1}), they are largely uncontaminated by other processes (e.g., star formation) and X-rays are less affected by intervening absorbing material compared to optical and ultraviolet light. To select our targets, we made use of the well-studied extragalactic fields of the Chandra Deep Field South (CDFS-S), the Cosmological Evolution Survey (COSMOS), the UKIDSS Ultra Deep Survey (UDS) and SSA22. These fields have been covered by deep multi-wavelength observations, including high-quality X-ray observations, making them ideal for selecting AGN with known redshifts, as well as charactering the host galaxy properties of these rapidly growing black holes.

Harrison et al. (2016) contains data for 89 X-ray AGN, of which 79 were observed with KMOS (new data) and 10 were observed with SINFONI (archival data). Of these, 54 were selected to observe the [O III] emission-line doublet and 35 were selected to observe the Hα and [N II] emission lines (see Figure 2). Crucially, these targets have X-ray luminosities that are representative of the parent X-ray AGN population and therefore can be used to understand the emission-line kinematics of this population as a whole. This is an improvement over most previous IFU studies of high-redshift AGN that have observed small numbers of highly selected targets, making it difficult to understand how representative they are.

The KMOS observations were carried out using an ABA sequence (where A is on-source and B is on-sky). Each target was observed with on-source integration times between roughly 1.5 and 2.5 hours. These first KASH*z* observations were very successful. When only considering the 82 targets with reliable archival redshifts, 72 of them (88 %) were detected in emission lines. Example KMOS data are shown for three targets in Figure 3. The lower panels show galaxy-integrated [O III] emission-line profiles and the upper panels show two-dimensional spectra, over the same wavelength region, for each of the 14 KMOS IFU slices. From only these examples, it can be seen that there is a wide variety in the shapes of the emission-line profiles as well as their spatial extents and velocity structure.

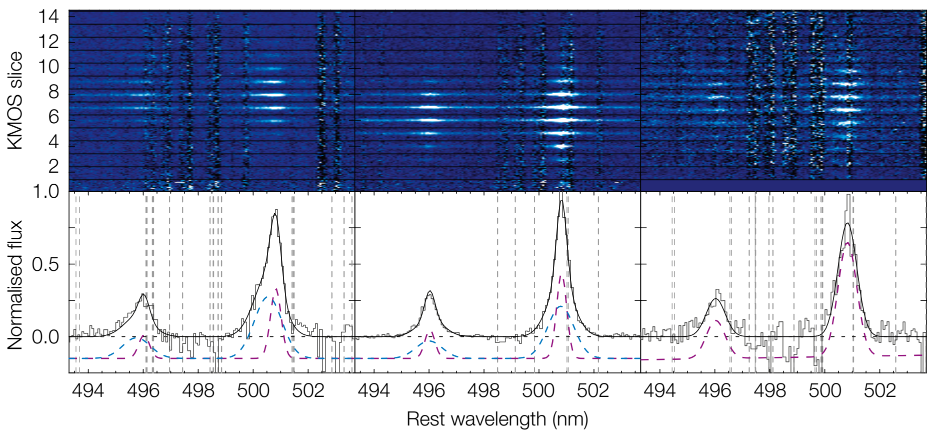

Figure 3. KASH*z* data for three example AGN-host galaxies centred around the [O III] 4959, 5007 Å emission-line doublet. Upper: The two-dimensional spectra from each of the 14 KMOS IFU slices. Lower: One-dimensional spectra created by summing over the spatial pixels within each IFU. The vertical dotted lines show the position of skylines. The black curve shows the fits to the emission-line profiles. Broad asymmetric emission-line profiles are indicative of warm, ionised outflows (see blue dashed curves); red dashed lines show the narrow emission line fits.

The first two examples in Figure 3 show broad underlying components in their [O III] emission-line profiles, indicating the presence of warm ionised outflows in the host galaxies of these X-ray AGN. The power of our survey is that we can constrain the prevalence of these ionised outflows in the context of the overall AGN population, following on from our work and of other groups at low redshift (see Figure 1). Furthermore, KASH*z* will enable us to assess how representative are the high-redshift AGN outflows that have been previously studied with near-infrared IFUs.

The prevalence of ionised outflows in high-redshift X-ray AGN host galaxies

One of the key aims of KASH*z* is to constrain the prevalence of ionised outflows in the host galaxies of high-redshift AGN. Following a similar approach to the Mullaney et al. (2013) study of z < 0.4 AGN, we set out to assess how common broad and asymmetric [O III] and Hα emission-line profiles are. These broad and asymmetric emission-line profiles are key indicators of warm, ionised outflows (see Figure 3). For example, Figure 4 shows a cumulative distribution of the overall [O III] velocity widths of the KASH*z* AGN extracted from the galaxy-integrated spectra (examples in Figure 3). These velocity widths are calculated by taking the velocity width between the 10th and 90th percentiles of the emission-line fluxes. Velocity widths of greater than 600 km s^{-1} are attributed to outflowing or highly turbulent material because even the most massive galaxies rarely reach these velocities from galaxy dynamics alone (see shaded region in Figure 4). We find that half of the sample observed in [O III] exhibit these or greater velocities. This finding implies that around half of X-ray luminous AGN host warm, ionised outflows that dominate their emission-line gas. Outflows that are less dominant in the overall kinematics will be even more common.

We have compared the prevalence of warm, ionised outflows in our high-redshift AGN sample with a luminosity-matched sample of z < 0.4 AGN taken from Mullaney et al. (2013). We observed a remarkable similarity between the distributions of ionised gas velocities between the two samples (see Figure 4). This result implies that, for a fixed black hole accretion rate, these outflows are very similar at both early and late epochs. However, due to a higher fraction of galaxies hosting rapid black hole growth at early times (see Figure 1), our results imply that the most extreme ionised outflows were more prevalent in the past.

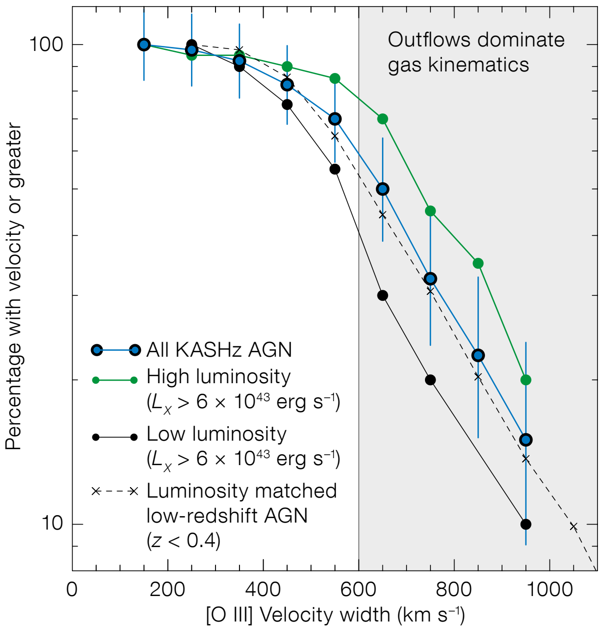

Figure 4. Cumulative histogram of the [O III] emission-line velocity widths for the z = 1.1–1.7 KASHz AGN observed so far, and a luminosity matched sample of low redshift AGN. Very high velocities of > 600 km s^{-1} indicate that the warm, ionised gas kinematics are dominated by outflows or high levels of turbulence (shaded region).

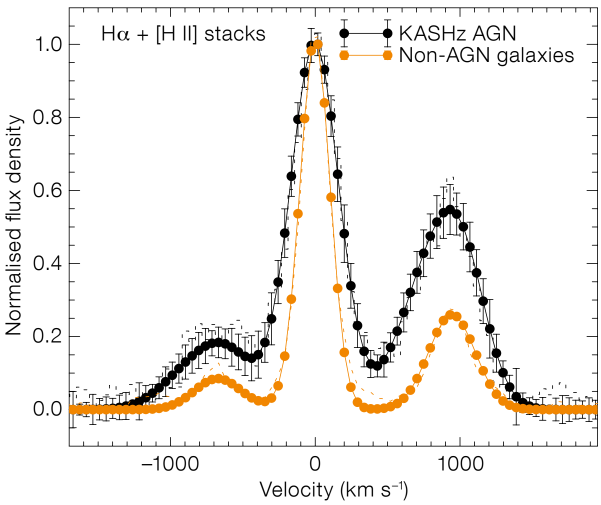

Figure 5. Stacks of the Hα and [N II] emission-line profiles for the z = 0.6–1.1 KASHz AGN observed so far (black curve) and a redshift-matched comparison sample of star-forming galaxies (orange curve) taken from the KROSS survey (Stott et al., 2016).

The drivers of ionised outflows

One of our key questions is what drives the most powerful outflows in high-redshift galaxies? We provide some initial insight in Harrison et al. (2016). For example, we found that high-velocity outflow features are about twice as common in the half of the sample with the most powerful (luminous) AGN compared to the less powerful half. Comparison of the green and black lines in Figure 4 demonstrates this result. This finding provides some evidence that the prevalence of outflows is increased in the host galaxies of the most rapidly accreting black holes.

We also compared the Hα and [N II] emission-line profiles of our AGN with a redshift-matched sample of star-forming galaxies with no clear signs of ongoing AGN activity (see Figure 5), taken from the KMOS Redshift One Spectroscopic Survey (KROSS; Bower & Bureau, 2014; Stott et al., 2016). The emission-line profiles are clearly broader in the host galaxies of the luminous AGN, implying that the prevalence of ionised outflows is increased. This effect still appears to hold true when taking into account the different galaxy masses of the two samples (see Harrison et al. [2016] for details). We can look forward to more direct evidence of the physical processes that drive these ionised outflows (e.g., radio jets versus AGN-driven winds, etc.) in future papers which exploit the full KASHz sample as well as multi-wavelength complementary datasets.

Ongoing work and prospects

We have presented the background and first results of KASHz. However, this is an ongoing project. By combining the excellent quality IFU data from KMOS and SINFONI, with the archival data available for our targets, we will be able to investigate a wide array of scientific questions. These include, how do the morphologies and energetics of the identified outflows compare to host galaxy and AGN properties, such as accretion rates, masses and star formation rates and what physical processes drive these outflows? These are key questions to address in order to constrain models of galaxy formation. Furthermore, as the observations continue, we are building up a larger sample of objects that, as well as increasing the parameter space covered by these objects, will provide the strongest statistics to date on the prevalence, properties and impact of ionised outflows in the host galaxies of high-redshift AGN.

Acknowledgements

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