VLT-SINFONI observations of Mrk 609 - A showcase for X-ray active galaxies chosen from a sample of AGN suitable for adaptive optics observations with natural guide stars

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Abstract

We will present first results of ESO-VLT AO-assisted integral-field spectroscopy of a sample of X-ray bright AGN with redshifts of $0.04 < z < 1$. We constructed this sample by cross-correlating the SDSS and ROSAT surveys and utilizing typical AO constraints. This sample allows for a detailed study of the NIR properties of the nuclear and host environments with high spectral resolution on the 100 pc scale. These objects can then be compared directly to the local ($z < 0.01$) galaxy populations (observed without AO) at the same linear scale. As a current example, we will present observations of the $z = 0.034$ Seyfert 1.8 galaxy Mrk 609 with the new AO-assisted integral-field spectrometer SINFONI at the VLT. The successful observations show, that in the future - while having observed more objects - we will be able to determine the presence, frequency and importance of nuclear bars and/or circum-nuclear star forming rings in these objects and address the question of how these X-ray luminous AGN and their hosts are linked to optically/UV-bright QSOs, low-z QSOs/radio galaxies, or ULIRGs.

Key words: galaxies: active, galaxies: fundamental parameters (classification, colors, luminosities, masses, radii, etc.), galaxies: stellar content
PACS: 95.85.Jq, 98.54.Cm, 98.62.Lv

* Based on observations with the ESO VLT; 60.A-9041(A).
1 Introduction

A major cornerstone for extragalactic astronomy is the advent of adaptive optics (AO) assisted imaging and spectroscopy on large ground-based telescopes like the Very Large Telescope (VLT), offering a combination of (near) diffraction-limited resolving power and large light-collecting area of 8-10m class telescopes (e.g. Brandner & Kasper, 2005). In addition 3D spectroscopy allows to study both, the morphology and the chemical composition, as well as the dynamics of extragalactic objects at the same time, at an unprecedented depth.

1.1 Starburst/Seyfert composite galaxies

Despite the finding of an apparent coevolution of super massive black holes in the centers of galaxies and their galaxy bulges (hosts) (e.g. Page et al., 2001), the detailed nature of this interconnection remains mysterious. Is star formation triggered by the active galactic nucleus (AGN) due to radiation pressure and winds from the accretion disk, which disturb the interstellar medium (as discussed by van Breugel & Dey (1993) for 3C 285)? Or can a nuclear starburst component initiate the accretion process onto the black hole (Norman & Scoville, 1988)? Recently, in their classification study of IRAS selected ROSAT sources, Moran et al. (1996) discovered a class of starburst/Seyfert composite galaxies. They show optical spectra which are dominated by features of starburst galaxies, using the line diagnostics of Veilleux & Osterbrock (1987). Their X-ray luminosity, however, is typical for Seyfert 2 galaxies. A closer look at the spectra reveals some Seyfert-like features, e.g. [OIII]λ5007 is significantly broader than all the narrow emission lines in the optical spectrum and in some cases there is a weak broad Hα component. There appears a resemblance with narrow-line X-ray galaxies (e.g. Boyle et al., 1995), which also show spectra of composite nature. It is still not clear how their strong X-ray emission can be reconciled with the weak/absent optical Seyfert characteristics. The faintness of these objects in the X-ray as well as the optical domain did not allow to study them in detail so far.

Near infrared (NIR) studies, especially integral field spectroscopy, provide powerful means to investigate the (circum-) nuclear properties of the above described AGN. Besides the much lower dust extinction there are a number of NIR diagnostic lines (in emission as well as in absorption) to probe the excitation mechanisms and stellar populations in these objects. Among these are hydrogen recombination lines, rotational/vibrational transitions of H2, stellar features like the CO(2-0) and CO(6-3) absorption band heads and forbidden lines like [FeII] and [SiVI] (Hill et al., 1999, Mouri, 1994, Marconi et al., 1994).
1.2 Mining the sky: A sample of X-ray bright AGN

Multi wavelength sky surveys like the Sloan Digital Sky Survey (SDSS) and the ROSAT All Sky Survey (RASS) are very comprehensive databases to search in for targets suitable for very sensitive and high-resolution AO-assisted observations in the NIR.

In particular, a cross-correlation between the first data release of the SDSS (Abazajian et al., 2003) and the RASS (Voges et al., 1999) resulted in a sample of about 70 X-ray luminous AGN ($L_X \approx 10^{43} - 10^{45}$ erg s$^{-1}$) at redshifts between $z = 0.1$ and $z = 1$ (Zuther et al., 2004, 2005). Most optical counterparts of the X-ray sources turn out to be AGN (e.g. Giacconi et al., 2001). Furthermore, these X-ray luminous sources cannot be studied locally because of their small number density in the local universe (Hasinger, 1998). They are therefore ideal targets for adaptive optics observations. A subset of this sample is comprised of the composite galaxies described in Section 1.1. Our sample allows to study their optical/near-infrared properties in the above described framework. In the following we will present our first integral field observations of the composite galaxy Mrk 609 (Fig. 1).

Fig. 1. HST $V$-band image of Mrk 609 (from the study of Malkan, Gorjian & Tam, 1998). The SINFONI field of view is indicated (see Sect. 2).
From the subset of starburst/Seyfert composite galaxies we chose Mrk 609 (Rudy et al., 1988) (Fig. 1) as one of the closest and brightest (AO self referencing) objects for one of the science verification phase observations\textsuperscript{1} of the new AO-assisted integral field spectrometer SINFONI at the Very Large Telescope [Eisenhauer et al., 2003]. The observations presented in this contribution were taken in AO-mode with a 100 mas pixel scale and a field of view of $3 \times 3$ arcsec\textsuperscript{2}. The 2-dimensional image was sliced by small mirrors into 32 slitlets which then were reimaged onto one long pseudoslit and dispersed onto a $2k \times 2k$ detector. Using the filters $J$ and $H + K$, a spectral resolution of $R \sim 2000$ was achieved. Details of the data reduction will be presented in a forthcoming paper (Zuther et al. in prep.). In the following we will present very first results from this study.

Fig. 2. $H + K$ median continuum image from the reconstructed data cube. Contours are displayed to guide the eye. The image is $3'' \times 3''$ in size.

2.1 Overall properties

This dataset shows the wealth of information which can be retrieved from the integral field observation. Fig. 2 shows a median $H + K$ continuum image of the reconstructed 3-dimensional data cube. Shown are the inner $3'' \times 3''$ around the nucleus. At its redshift of $z = 0.034$, 1 arcsecond corresponds to about 700 pc\textsuperscript{2} and 1 pixel ($\approx 0.05$ arcsec) to about 40 pc. The shape of the

\textsuperscript{1} http://www.eso.org/science/vltsv/sinfonisv/xrayagn.html
\textsuperscript{2} Assuming $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_\Lambda = 0$, and $\Omega_m = 1$. 

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contours, which appear to be elongated towards the root points of the spiral arms (Fig. 1), suggests the possibility of the presence of a nuclear bar (cf. e.g. Martini et al. 2001). Fig. 3 shows a nuclear and off-nuclear $H + K$ spectrum. Some properties deserve mentioning:

- The nuclear spectrum is clearly reddened compared to the off-nuclear one. Reddening towards the nucleus due to the presence of dust is typically found in AGN (Glass & Moorwood, 1985).
- The nuclear Pa$\alpha$ line shows a broad component with a width of about 4000 km/s arising from the broad line region. This component is not visible in the off-nuclear spectrum.
- Around 1.8 $\mu$m the effect of degrading atmospheric transmission is visible.
- Stellar absorption features like the NaI $\lambda$2.206, 2.208 doublet, CaI $\lambda$2.263, CO(6-3), and CO(2-0) are visible, helping to estimate the stellar content.
2.2 Tracing the narrow-line emitting gas

The great advantage of integral field spectroscopy is the simultaneous availability of spatial and spectral information. This allows to generate spatial maps of spectral features of interest. The first three panels in Fig. 4 show the recombination lines Pa$\alpha$, Br$\gamma$, and HeI as tracers of star formation. This emission is extended and, besides the nucleus, is concentrated in a ring-like structure at a projected distance of about 500 pc. The morphology roughly follows the continuum contours of Fig. 2. Thus, we could be dealing with a starburst ring embedded in a nuclear bar. There is a plentiful number of examples of starburst rings in galaxies with and without nuclear activity (cf. Smith et al., 1999 and references therein) and which have comparable sizes.

![Fig. 4. Preliminary spatial distribution of prominent emission lines. The potential starburst ring is indicated by a thick ellipse in the Pa$\alpha$ map.](image)

Other species like the forbidden transitions [SiVI] and [FeII] are concentrated
on the nucleus in Fig. 4. High energetic nuclear emission is primarily able to penetrate deeply into the interstellar medium and produce regions which are partly ionized and where such transitions can be excited. The [FeII] emission is slightly extended, indicating also a connection with supernovae excited emission in the starburst ring.

Rotational/vibrational transitions of H$_2$ can be used to study the dominant excitation mechanisms in the circum-nuclear environment (e.g. Mouru, 1994). The emission lines originate in surfaces of molecular clouds exposed to stellar or nuclear radiation. Three major processes are considered: (1) excitation by X-ray or cosmic rays coming from the AGN; (2) shock excitation either from supernova winds or streaming motion; or (3) UV fluorescence from young stars. The first two processes are of thermal nature, whereas the third is non thermal. 1-0S(1) and the other detectable emission lines are also concentrated on the nucleus. Line ratios are used to estimate the level populations of H$_2$ in Mrk 609, indicating a thermal origin of the emission with a temperature of about 1900 K (Fig. 5, Zuther et al. in prep.). At the current stage of analysis, excitation due to X-rays also seems to be unimportant, because a number of other H$_2$ transitions which would be expected in the case of X-ray excitation (Tine et al., 1997), are not detected. This was already suggested by previous studies of a number of infrared galaxies (e.g. Koornneef & Israel, 1996).

Line ratios of hydrogen recombination lines (e.g. Pa$\alpha$ and Br$\gamma$) can be used to estimate the amount extinction. Assuming case-B recombination we find no significant extinction in the ring like structure. The nuclear ratios also give no significant extinction. At the nucleus, however, this value can be influenced by not-perfect separation of the narrow and broad component of the Pa$\alpha$ line. One can further use parts of the spectrum without prominent emission/absorption lines to generate a reddening map. Fig. 6 shows the circum-nuclear reddening using parts of the continuum in the H- and the K-band. The largest values of
reddening are found close to/at the nucleus and at the local Paα peaks at the tips of the bar within the putative starburst ring. This indicates the presence of dust and molecular material feeding the AGN or the star formation.

Fig. 6. Preliminary reddening map. Dark contours correspond to Paα emission, lighter contours to continuum emission.

### 3 Summary and conclusions

In this contribution we have presented SINFONI science verification observations of the starburst/Seyfert composite galaxy Mrk 609, which has been drawn from a sample of AO-suitable X-ray luminous AGN. AO-assisted integral field spectroscopy in the NIR providing simultaneous spatial and spectroscopic information enables the detailed study of the connection/feedback between star formation and nuclear activity by means of emission/absorption line diagnostics, 2-dimensional morphological, and kinematical analysis.

The presented observations indicate the presence of a nuclear bar and associated star formation in a starburst ring. The dominating central excitation mechanism for molecular hydrogen appears to be of thermal origin.

Further work on the spectral/spatial analysis will quantify the above statements and incorporation of complementary multi wavelength data (SDSS, ROSAT, CO(1-0); Zuther et al. in prep.) will give a better understanding of the feedback between nuclear activity and host galaxy environment in Mrk 609.
Expanding this study to other members of the sample will provide further insights into the nature of the class of starburst/Seyfert composites itself.

Acknowledgments

This work was supported in part by the Deutsche Forschungsgemeinschaft (DFG) via grant SFB 494.

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