Dissecting the Nuclear Environment of Mrk 609 with SINFONI – the Starburst-AGN Connection

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The new VLT instrument SINFONI gives us a view onto the circumnuclear properties of AGN in unprecedented detail, even beyond our local Universe. As a science verification target, the showcase object Mrk 609 demonstrates impressively the necessity of adaptive optics assisted integral-field spectroscopy in order to distinguish between Seyfert and starburst characteristics on nuclear scales.

Fuelling of nuclear activity

The presence of the Seyfert phenomenon is supposed to originate in the accretion of matter onto a super-massive black hole (SMBH) in the centre of a galaxy. Nuclear activity is composed of nuclear starbursts and Seyfert-like emission. The fuel necessary for driving this activity has to be transported from galactic scales (~ 10 kpc) down to nuclear scales of ~ 10 pc. We are still far from understanding the detailed processes that create non-axisymmetric potentials leading to the dissipation of angular momentum. Such instabilities are needed for the gas and stars to fall towards the nuclear region. However, considerable theoretical as well as observational effort has been made to understand these processes (e.g. Shlosman et al. 1990; Knapen 2005). We can distinguish external and internal triggers of the fuelling process:

External triggers are related to the environment of galaxies and gravitational interaction. Non-axisymmetry, which can lead to loss of angular momentum, can result from galaxy interactions. For Ultra Luminous Infra-red Galaxies (ULIRGs), which show the most extreme cases of infrared nuclear activity, there is intriguing evidence for a connection between galaxy interaction and nuclear activity.

Internal triggers are based on instabilities generated from within the host. For example a two-step process has been proposed that is able to sweep the interstellar medium (ISM), via a stellar bar, from large scales into a disk of several hundred pc in radius. In the second step, further instabilities (bar-within-bar) drive the material close to the nucleus, until viscous processes take over the angular momentum transport.

While in quiescent galaxies, extensive star formation appears to be related to large-scale bars, the observational evidence for non-axisymmetry-related nuclear activity is not as clear for Seyfert galaxies. A slight but significant increase in the galactic-bar fraction of active galaxies has been found when compared to non-active galaxies. This does not appear to be the case for nuclear bars. Furthermore, there are a considerable number of AGN that show no signs of the presence of a bar, as well as of non-active galaxies that do possess bars.

Mrk 609: a starburst/Seyfert composite galaxy

Mrk 609 is classified as a *starburst/Seyfert composite* galaxy. This class of AGN appears to be best suited to study the starburst-AGN connection, since the AGN and starburst components present themselves at the same level of activity (Moran et al. 1996). Composite galaxies can be characterised by optical spectra which are dominated by starburst features, while the X-ray luminosity and its variability are typical for Seyfert galaxies. The former property is based on the emission-line diagnostic diagrams by Baldwin, Phillips and Terlevich (BPT 1981). Close inspection of the optical spectra often reveals some weak Seyfert-like features, e.g. [O III] being significantly broader than all other narrow lines, or a weak broad Hα component. There is a resemblance to narrow-line X-ray galaxies, which also show spectra of composite nature. Their soft X-ray spectra are flat, but it is still not clear how this strong and hard X-ray emission can be reconciled with the weak optical Seyfert characteristics. The faintness of these objects in the X-ray, as well as in the optical domain, has prevented them from being studied in detail so far.

The SINFONI observations

Near-infrared imaging spectroscopy (cf. Gillessen et al. 2006) has considerable advantages over visible wavelength spectroscopy. Besides the much smaller dust extinction, there are a number of NIR diagnostic lines that probe the stellar and non-stellar content in Mrk 609. Among these are hydrogen recombination lines, ro-vibrational transitions of H_2, stellar features like the CO(2–0) and CO(6–3) absorption band heads, as well as forbidden lines like [Fe II] and [Si VI].

The data (Zuther et al. 2007) have been acquired during the science verification phase of SINFONI in August/October 2004. For the first time we have spatially resolved the circumnuclear environment on the scale of 270 pc in the *J* and *H* + *K* bands (Figure 1). The morphology is complex, and the continuum image reveals a stellar bar-like structure superposed on the point-like Seyfert nucleus (Figure 1a). The distribution of hydrogen recombination emission (Paα) is clumpy and peaks at the tip where the potential bar meets the spiral arms and in regions along the minor axis (Figure 1b). The presence of nuclear broad Paα and [Si VI] are clear indicators of the accretion of matter onto a nuclear supermassive black hole. The distribution of molecular hydrogen follows the continuum shape, while that of [Fe II] is aligned with the minor axis of the continuum and with the H-recombination emission (Figure 1c and 1d).

The well established BPT emission line diagnostics at visual wavelengths fail for regions with considerable extinction. Recently it was found that an analogous NIR line diagnostic diagram, using [Fe II]/Paβ and H_2/Brγ line ratios, allows us to distinguish between starbursts (photoionisation excitation), AGN (mixed excitation), and LINERs (shock excitation). In this diagram, the nucleus of Mrk 609 shows signs of LINER activity (Figure 2). Shock-driven excitation can be recognised by its high [Fe II]/Paβ and H_2/Brγ values. Our integral-field data clearly resolve the nuclear and starburst activity in the central kiloparsec. Extinction appears to play no crucial role in this region, since the H-recombination line ratios are consistent with unreddened case-B values. This is furthermore supported by the strong Lyα emission in the ultraviolet.

The different regions characterised by clumpy Paα emission (Figure 1b) clearly follow a trend from a LINER-like value at the nucleus to a starburst-like value in the most distant North-eastern region (data point 5 in Figure 2). The circumnuclear regions (data points 2, 3, and 4) fall in the domain of mixed excitation. In contrast to our nuclear classification, the line ratios extracted from the total field of view resemble those of a typical Seyfert galaxy. The same Seyfert characteristics are obtained from the large aperture Sloan Digital Sky Survey visual spectrum. This demonstrates how the choice of spatial scales to be studied can influence the resulting classification. Our LINER classification of Mrk 609, together with published data on variability of its non-stellar NIR emission, might be explained with the duty-cycle hypothesis, in which short-lived accretion events occur periodically and lead to the appearance of Seyfert features in the high state and low-ionisation (shock-driven) emission features in the low state. In order to verify this possible scenario, multi-epoch SINFONI observations are needed.

The small spatial scales which SINFONI resolves on Mrk 609 allow for an investigation of the transport of matter within the central one kiloparsec. Obviously, Mrk 609 shows no signs of external triggers (i.e. interaction with companion galaxies). The presence of a nuclear bar-like stellar structure, as well as the clumpy morphology of the emission line gas, fits into the picture of internal triggers, feeding the AGN and circumnuclear star formation. However the chicken-and-egg problem – whether the star for-mation activates the accretion onto the SMBH or AGN feed-back initiates nearby starburst activity – remains open.

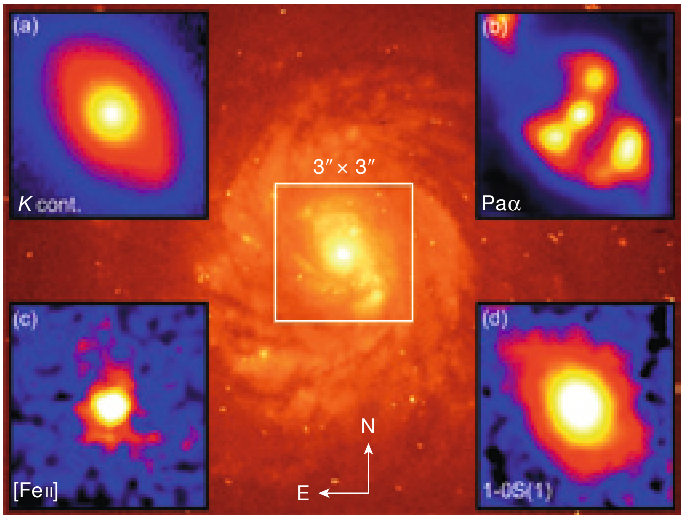

Figure 1: Hubble Space Telescope (HST) F606W-band image of Mrk 609 (centre, from Malkan et al. 1998) overlayed with SINFONI maps of various spectral features: (a) *K*-band continuum map, (b) Paα map, (c) [Fe II] 1.275 μm, and (d) 1-0 S(1) molecular hydrogen. The SINFONI field of view is indicated by the white box in the HST image.

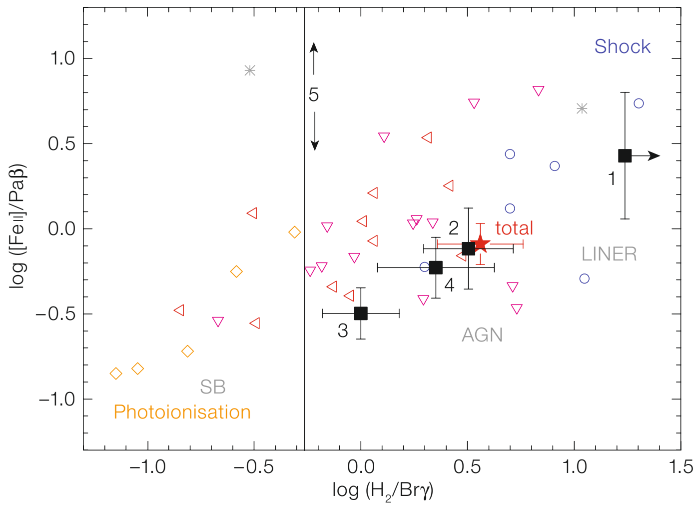

Figure 2: Line ratios of [Fe II] 1.257 μm/Paβ and 1-0 S(1) 2.121 μm/Brγ. Activity types (starburst (SB), AGN and LINER) are indicated. Filled symbols represent our SINFONI measurements of five distinct regions of Mrk 609, as well as of the total field-of-view (red star). On account of missing *J*-band data, region 5 is only accurately located along H_2/Brγ. Open symbols correspond to literature values; orange diamonds represent starburst galaxies; red left triangles Seyfert 1 galaxies; magenta headlong triangles Seyfert 2s; blue circles LINERs; and grey asterisks supernovae. The diagram is interpreted as displaying the transition from pure photoionisation (lower left corner) to pure shock driven emission (upper right).

Outlook

The starburst/Seyfert composite nature of Mrk 609 can be disentangled into distinct regions of star formation and strong nuclear activity. Probably, this is true for most composite galaxies. Whether relationships between the occurrence of dynamical instabilities, star formation, and AGN activity are causally linked can only be determined with AO-assisted imaging spectroscopy (e.g. SINFONI) observations on a larger sample of this class of objects. Moving beyond the backyard of our Milky Way towards larger look-back times and stronger nuclear activity, allows for a comparison with local AGN on the same physical scales. Then we are able to study scenarios such as whether circumnuclear starburst features generally accompany the cores of galaxies with even stronger nuclear activity, i.e. pure Seyferts and/or QSOs, or if enhanced star formation is a distinct phase in the evolution of AGN (e.g. Lípari and Terlevich 2006). However, resolving the central region of these objects on the 100 pc scale is fundamental for these studies.

References

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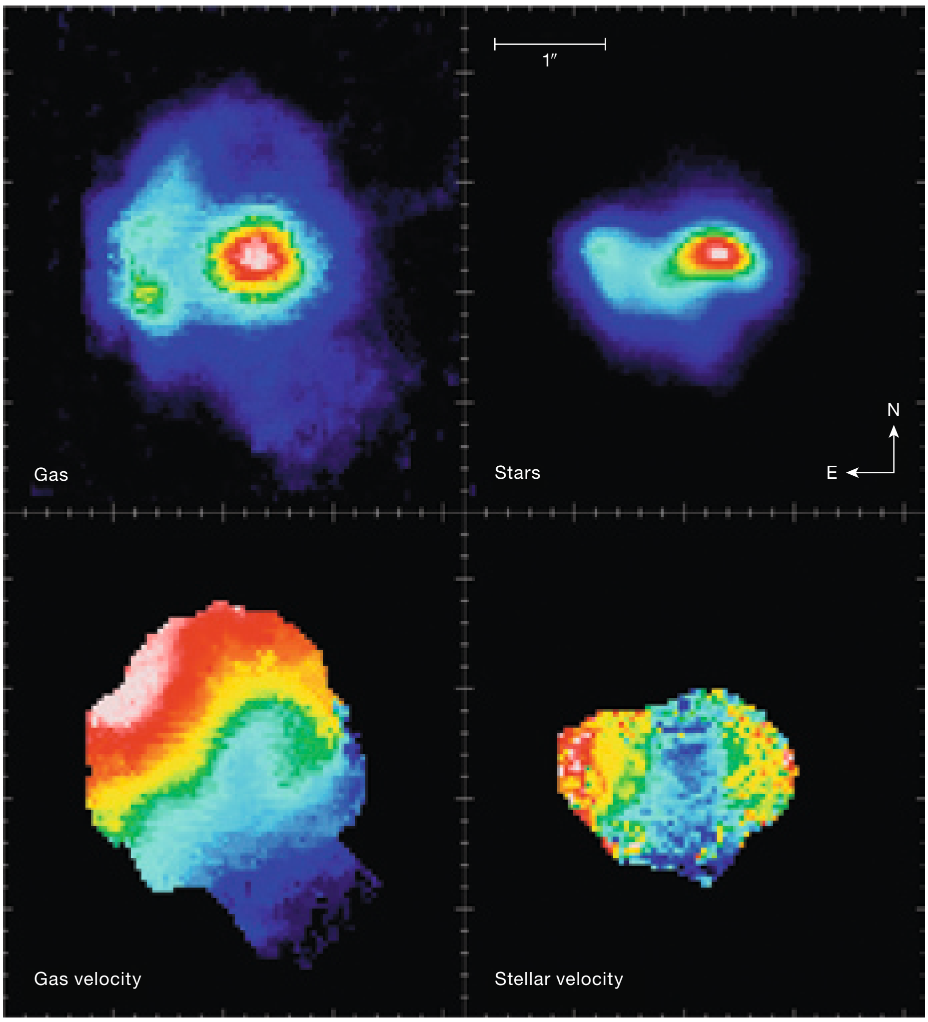

The famous luminous infra red galaxy merger Arp 220 is shown here in more results from VLT SINFONI, this time used in tandem with the Laser Guide Star System (LGS). The LGS provides real-time adaptive optics correction using an artificial, laser-fed star to correct the distortions of the atmosphere. The two nuclei of Arp 220, separated by 1.0 arsec, were resolved, the brighter to the west (right) and the more diffuse to the east. The upper images (where the brightness is colour-coded) show the appearance in molecular gas (left) and stellar light (right). The two lower images show the behaviour of the velocities of the gas (left) and the stars (right); the colour-coded images here depict matter moving towards the observer (in blue) and moving away (red). It is apparent that the stars and the gas move differently: the stars in two counter-rotating discs and the gas in a larger-scale disc. The image is taken from ESO PR 27/07, which provides more details.