SINFONI on the Nucleus of Centaurus A

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The prominent radio galaxy Centaurus A is the closest active galaxy and a prime opportunity to study the central supermassive black hole and its influence on the environment in great detail. We used the near-infrared integral field spectrograph SINFONI to measure Centaurus A's black hole mass from both stellar and gas kinematics. This study shows how the advance in observing techniques and instrumentation drive the field of black hole mass measurements, and concludes that adaptive optics assisted integral field spectroscopy is the key to identifying the effects of the active galactic nucleus on the surrounding ionised gas. The best-fit black hole mass is $M_{BH} = 4.5^{+1.7}_{-1.0} \times 10^7 M_\odot$ (from H_2 kinematics) and $M_{BH} = 5.5 \pm 3.0 \times 10^7 M_\odot$ (from stellar kinematics; both with 3σ errors). This is one of the cleanest gas versus star comparisons of a black hole mass determination, and brings Centaurus A into agreement with the relation of black hole mass versus galaxy stellar velocity dispersion.

During the last few years it has been realised that most, if not all, nearby luminous galaxies host a supermassive black hole in their nucleus, with masses in the range of one million to ten billion solar masses. The black hole mass (M_{BH}) is tightly related to the mass or luminosity of the host stellar spheroid, or bulge, and with the velocity dispersion σ (called the M_{BH}–σ relation) of the stars therein. These correlations have an amazingly low scatter, perhaps surprisingly low, since the black hole and the bulge probe very different scales. These facts indicate that the formation of a massive black hole is an essential ingredient in the process of galaxy formation.

Centaurus A — a special case?

At a distance of less than 4 Mpc NGC 5128 (Centaurus A, hereafter Cen A) is the closest giant elliptical galaxy, the closest active galaxy and the closest recent merger. Cen A hosts an active galactic nucleus revealed by the presence of a powerful radio and X-ray jet. Although this is one of the nearest supermassive black holes, its mass was long under debate (see Neumayer, 2010, for a review). Recent stellar dynamical measurements and modelling by Silge et al. (2005) result in a black hole mass of 2.4×10^8 solar masses, in agreement with the gas dynamical study of Marconi et al. (2001), who found 2×10^8 solar masses (although with a large error bar, depending mainly on the unconstrained inclination angle of the modelled gas disc).

This measurement of the black hole mass placed Cen A almost an order of magnitude above the M_{BH}–σ relation, and made it one of the largest outliers to this relation. The question was whether this is an intrinsic property of Cen A or whether the ground-based seeing-limited observations were not sharp enough to resolve the "sphere of influence" of Cen A's black hole. This is the radius where the black hole dominates the gravitational potential, and, according to the mass predicted from the M_{BH}–σ relation, would be 0.3 arcseconds — not resolved by seeing-limited observations.

Adaptive optics to the rescue

In 2003 we embarked on a comprehensive study of the nucleus of Cen A using the near-infrared imager and spectrograph NAOS–CONICA (NACO) at the VLT. Guiding on the dust-enshrouded nucleus with the unique infrared wavefront sensor that NACO possesses, we obtained images and long-slit spectra at or close to the diffraction limit of the VLT. This study showed that adaptive optics actually works and is applicable to active galactic nuclei (AGN; Häring-Neumayer et al., 2006). It resulted in a black hole mass about a factor of three lower than previous measurements. However, with only four slit positions we were not able to constrain fully the inclination angle of the modelled gas disc.

An ideal combination

With the arrival of SINFONI at the VLT, the study of black holes in galaxy centres made a big leap forward. SINFONI provides integral field spectroscopy at adaptive optics (AO) resolution (Eisenhauer et al., 2003; Bonnet et al., 2004). An ideal combination for studying galaxy centres in great detail! We obtained high signal-to-noise 3D spectra in *J*-, *H*- and *K*-bands (see Figure 1) with two different spatial scales: (i) 0.250 × 0.125 arcseconds (250-milliarcsecond scale) with a field of view of 8 × 8 arcseconds, and (ii) 0.10 × 0.05 arcseconds (100-milliarcsecond scale) with a field of view of 3.2 × 3.2 arcseconds. These spectra show a wealth of gas emission and stellar ab-sorption lines, and enabled us to extract the morphology and kinematics for dif-ferent gas species (Figure 2) as well as the stars, simultaneously. The 100-milliarcsecond data have a spatial resolution of 0.12 arcseconds (full width at half maximum, FWHM) and comfortably re-solve the sphere of influence of the putative black hole.

The SINFONI data reveal vividly how the flux distribution and kinematics in the gas change when going from high to low excitation states. When comparing the velocity fields of [Si VI], [Fe II], and H_2 (middle panels in Figure 2), one notices that the velocity field of [Si VI] consists of two major components: rotational motion around the nucleus (marked with a cross) and translational motion along the jet direction (P.A. = 51°). The non-rotational motion along the jet is less severe, but still remarkable in [Fe II]. The situation is different for molecular hydrogen: the kinematics of H_2 is completely dominated by rotational motion. The molecular gas seems to be well settled in a rotating disc around the black hole without suffering major distortions by the jet. For this reason, we focus on H_2 as the dynamical tracer for the central mass concentration.

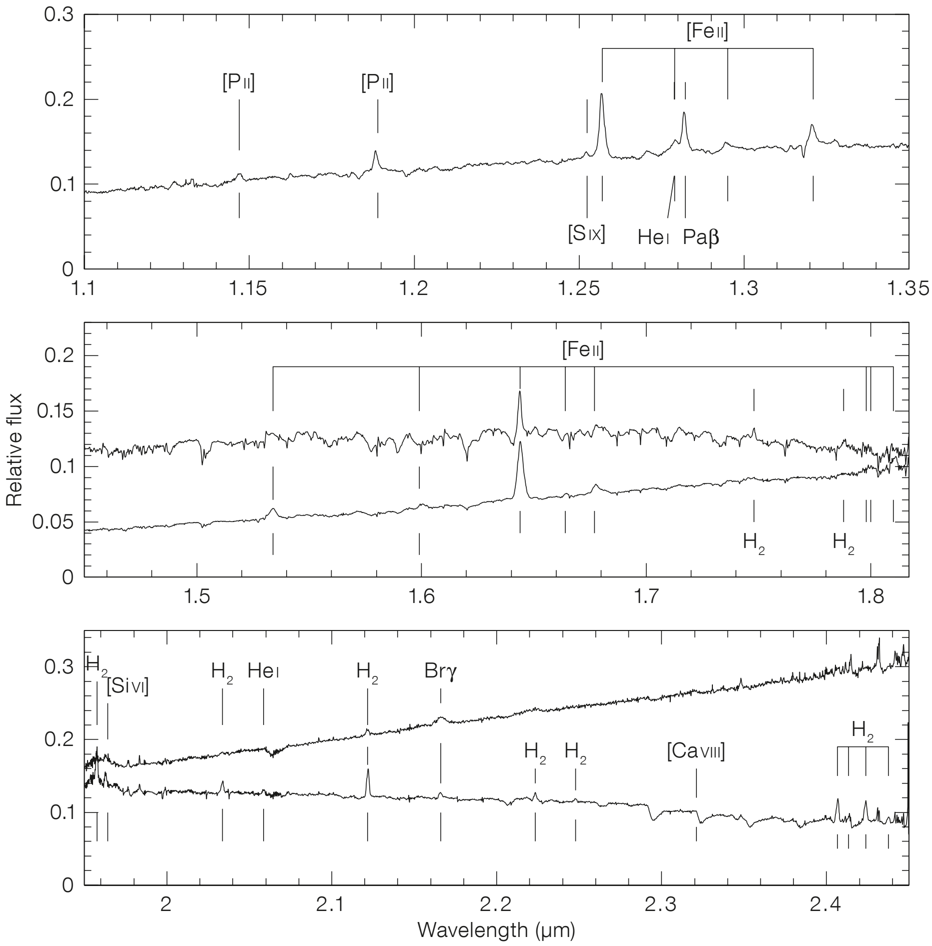


Figure 1. SINFONI spectra in *J*-, *H*- and *K*-band (from top to bottom) of the central 3 × 3 arcsecond circumnuclear region of Cen A. For *H*- and *K*-bands the spectrum is extracted in two different regions, one including the central source (lower line in *H*-, upper line in *K*-band) and one excluding it, i.e. showing the stellar contribution (upper line in *H*-band, lower line in *K*-band).

The SINFONI maps constrain the geometry of the gas disc much better than the few long-slits have done before. The disc is not flat, but appears warped, as indicated by the twist in the line-of-nodes. It connects well with the warped molecular gas disc at larger radii (Quillen et al., 2010). Moreover, the gas disc is consistent with an orthogonal jet-disc picture, and its orientation matches well with a dust disc identified from MIDI observations (Meisenheimer et al., 2007).

In addition to the gas kinematics we have also extracted stellar kinematics from the high signal-to-noise SINFONI *K*-band data. The near-infrared *K*-band spectral region is dominated by the strong stellar absorption feature of the 2.30-μm (2-0) ^{12}CO band head. At this wavelength, the galaxy spectrum is dominated by the light from cool and evolved giant stars. As a library of stellar templates, we used a set of eleven dwarf and giant stars (luminosity class II–V) of late spectral types (K–M), observed with the same instrumental setup as for the Cen A observations. As there is no evidence for a sudden change in the stellar population in the nucleus of Cen A, we assume that the stellar template is fixed and model the non-thermal continuum via additive polynomials, plus we include in the fit the additive contribution of a scaled version of the nuclear non-thermal spectrum (Figure 3). This approach allows us to reliably extract σ in the high resolution 100 milliarcseconds as observations down to a radius of 0.2 arcseconds, before the photon noise of the nucleus eliminates all stellar information from the spectra. For the kinematic extraction the emission from the highly ionised species of [Ca VIII] at 2.32 μm and an H_2 line at 2.35 μm was excluded from the fits (see Figure 3).

The nuclear stellar rotation (Figure 4) is counter-rotating (by about 180°) with respect to the regular H_2 nuclear gas rotation (Figure 2). The stars rotate with a maximum velocity of 25 km/s and are thus much slower than the gas, which reaches a maximum velocity of 130 km/s at $R \approx 0.5$ arcseconds. This indicates that the recent gas acquisition was not able to produce a significant fraction of stars near the nucleus. This is consistent with the lack of evidence for any change in the nuclear stellar population of Cen A.

Modelling the black hole mass: from gas kinematics…

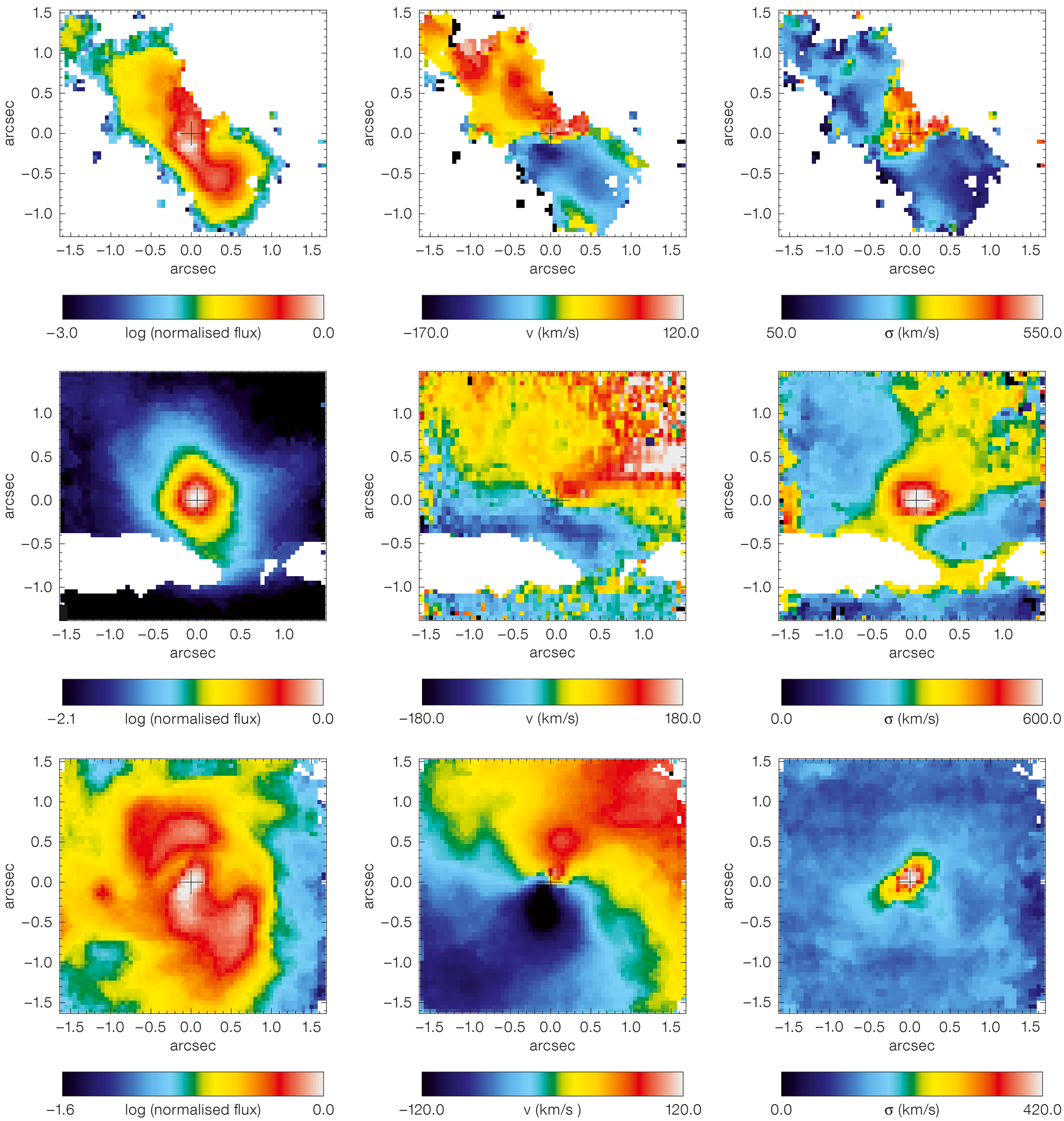
In order to explain the H_2 gas motions seen in the centre of Cen A we construct a kinematic model, where we assume that the gas moves in a thin disc solely under the gravitational influence of the surrounding stars and the expected central black hole. The stellar potential is derived from a composition of NACO, NICMOS, and 2MASS *K*-band images of Cen A. Under the assumptions of spherical symmetry and combined with a dynamically-derived stellar mass-to-light ratio, this gives a three-dimensional mass model, setting the stellar velocity contribution to the dynamical model. Since the observed velocity dispersion of the H_2 gas at the nucleus of Cen A exceeds the mean rotation by more than a factor of two, we need to account for the velocity dispersion in the dynamical model.

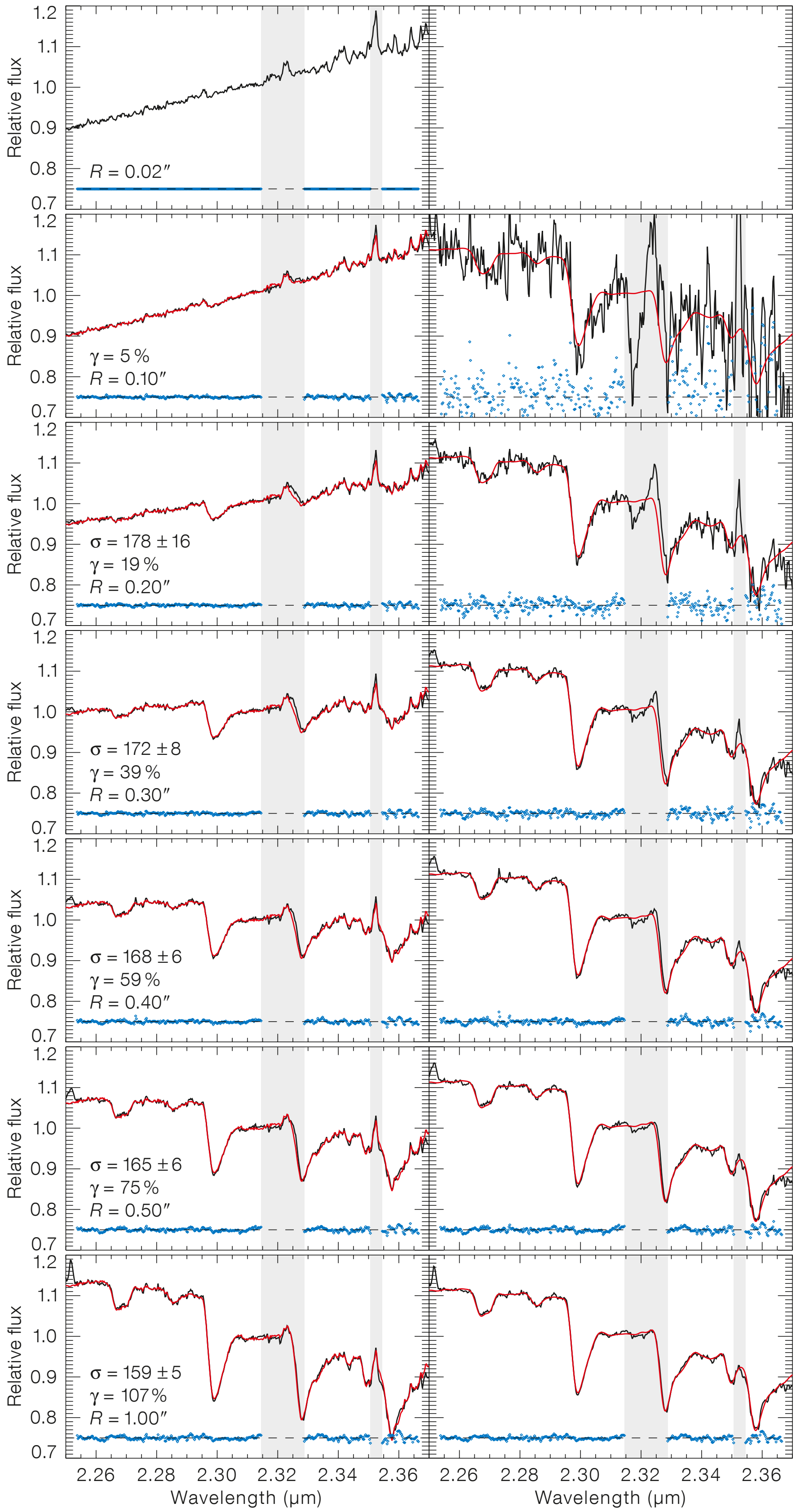
We model the kinematics via a tilted-ring model, where the inclination angle and position angle of the gas disc are a function of radius. The orbits of the gas at each radius remain circular, but neighbouring orbits are not necessarily in the same plane. The gas disc geometry changes from coplanar to warped. We calculate a grid of possible models for varying disc inclination and central black hole mass to obtain the set of values that best match the observed data (Figure 4). The best-fitting black hole mass in our tilted-ring model to the H_2 kinematics is $M_{BH} = 4.5^{+1.7}_{-1.0} \times 10^7\ M_\odot$ for a median disc inclination of 34° ± 4° (error bars are given at the 3σ level).

…and stellar kinematics

For the stellar dynamical modelling, the integral field, high spatial resolution SINFONI observations are essential to tightly constrain the black hole mass

Figure 2. Flux, velocity, and velocity dispersion maps (left to right) of the [SiVI], [FeII], and molecular hydrogen line emission (top, middle, and bottom, respectively). Note the different morphology and kinematics of the ionised gas ([SiVI] and [FeII]) *vs.* the molecular gas.





and stellar orbital distribution. However, they are not sufficient as they sample only a small fraction of the half-light radius of Cen A (R_e = 83 arcseconds in the *K*-band). For this reason we complemented our data by the *K*-band kinematics obtained with the Gemini Near Infrared Spectrograph at Gemini South by Silge et al. (2005), which are in very good agreement with the SINFONI data outside the central 2 arcseconds. The stellar kinematics are fit by axisymmetric three-integral orbit-superposition models (Figure 5) to determine the best-fitting values for the black hole mass M_{BH} = 5.5 ± 3.0 × 10^7 (3σ errors) and mass-to-light ratio M/L_K = (0.65 ± 0.15) in solar units. This black hole mass value is in very good agreement with the determination from the kinematics of molecular hydrogen. This provides one of the cleanest gas versus star comparisons for a black hole mass determination, due to the use of integral field data for both dynamical tracers and due to a very well-resolved black hole sphere of influence. Moreover, it brings Cen A into agreement with the M_{BH}–σ relation (Figure 6).

Lessons learned

The development of the black hole mass measurement in Cen A over the past eight years reflects the advance in observing techniques, especially in the near-infrared. High spatial resolution observations are crucial to determine the influence of the central black hole on the gas and stellar kinematics. Adaptive optics actually works! With the advent of near-infrared adaptive optics assisted spectrographs, such as NACO at the VLT,

Figure 3. Radial variation in the spectrum of Cen A in the 100-milliarcsecond SINFONI observations. Left-hand column: different panels show the observed spectra (black solid line) obtained by co-adding the spectra of the spaxels contained within circular annuli of radius *R* and one pixel width (0.05 arcseconds). The best-fitting model (red solid line) consists of the stellar template plus a fourth degree additive polynomial, plus a scaled copy of the non-thermal nuclear spectrum (top panel). The residuals are shown at the bottom of each panel with the blue dots. Right-hand column: the convolved optimal template (red solid line) is compared to the observed spectrum after subtraction of the nuclear spectrum and polynomial contributions (black solid line). The blue dots show the residuals.

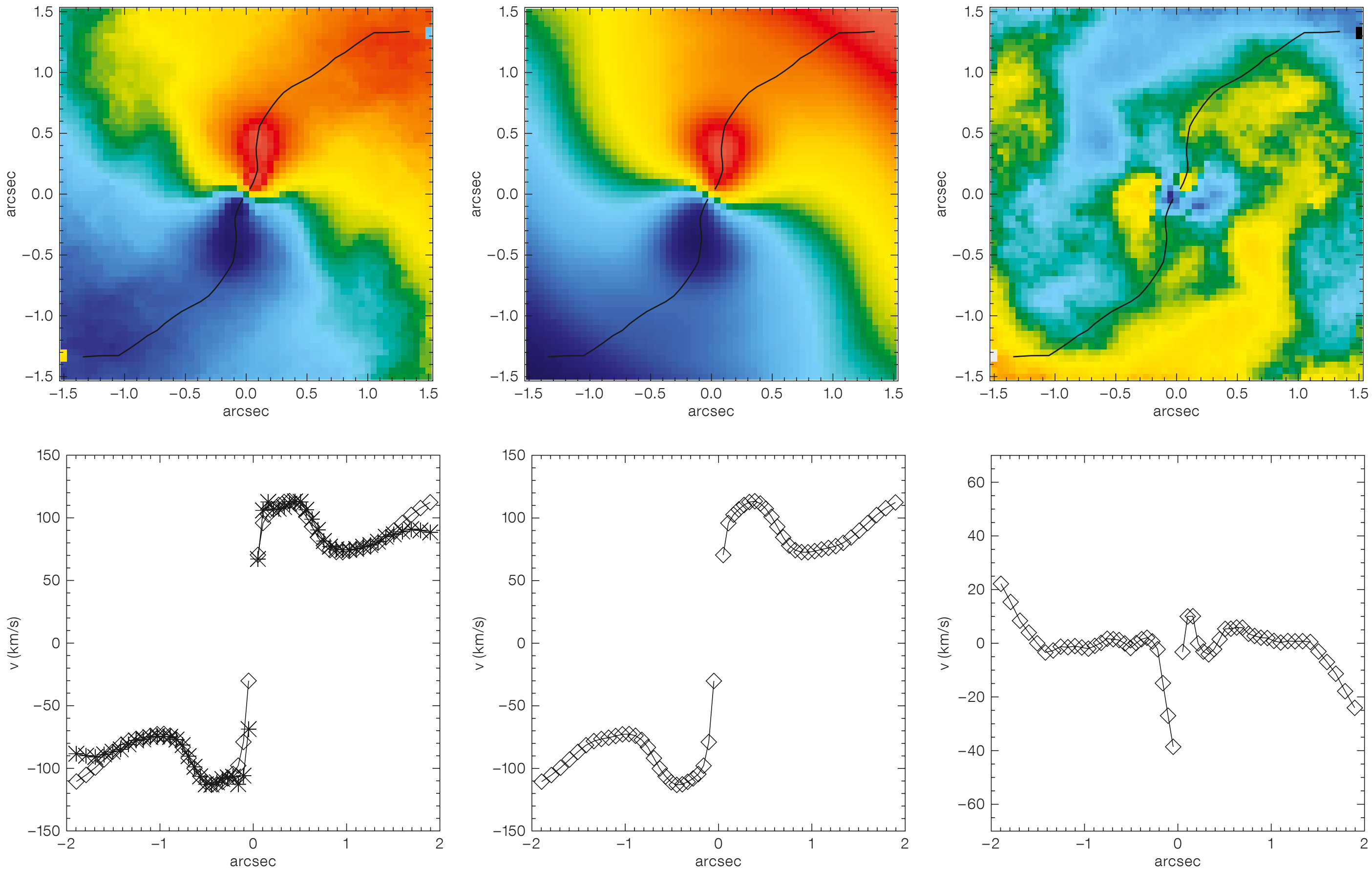


Figure 4. Symmetrised velocity map (upper left) in comparison to the model (upper middle; M_{BH} = 4.5 + 1.7 × $10^7 M_\odot$, median disc inclination 34°). The residual (data-model) is shown in the upper right panel. The velocity curves in the bottom panels are extracted along the line-of-nodes (overplotted on the velocity maps), and therefore represent the peak velocity curves; the three panels show the observed and model points, the model points only and the residuals. The diamonds correspond to the model velocity curve while the asterisks correspond to the data. The agreement is very good along the line of nodes. The mismatch in data and model for radii beyond r ~ 1.7 arcseconds is likely due to the fact that the inclination angle of the modelled gas disc is not well represented in the outermost parts. This has no impact on the derived black hole mass (taken from Neumayer et al., 2007).

even dust-enshrouded galaxy nuclei became accessible at a spatial resolution of 0.1 arcseconds. This becomes even more powerful when combined with integral field spectroscopy, as in SINFONI. Mapping the gas and the stars in 3D allows the morphology and kinematics of different gas species, plus the stars, to be compared directly and simultaneously. Having this powerful tool in hand, the influence of the inner jet on the kinematics of the ionised gas in Cen A could be revealed, and, moreover, molecular hydrogen could be identified as the ideal gas tracer for the central gravitational potential. The physical state of the gas is therefore very important when using it as a tracer for the dynamical models. The decrease of the value of the black hole mass from Marconi et al. (2001) to Neumayer et al. (2007) was due to the increase in spatial resolution, plus the fact that the kinematic tracer changed from ionised gas to molecular hydrogen.

The presence of an AGN can definitely influence the kinematics of the gas, while the stellar kinematics should be unchanged by this. However, the extraction of the stellar kinematics from the spectral absorption features becomes increasingly difficult in the close vicinity of the AGN, as the AGN continuum dilutes the stellar absorption lines. This is the main difference in the analysis of Silge et al. (2005) and Cappellari et al. (2009). While Silge et al. (2005) first subtract the AGN contribution and then fit the stellar line-of-sight-velocity distribution, Cappellari et al. (2009) include the fit of the AGN continuum in the extraction of the stellar kinematics. This is a very interesting lesson that we learned from Cen A, and we should be cautious when extracting kinematics from other, more distant objects. We also learned that high signal-to-noise data are crucial to extract the stellar kinematics reliably down to small radii. Cen A is indeed the closest AGN and at the same time it is very complex. Every leap in instrumentation development is likely to reveal more complex substructures. This warrants our continuous attention, in order to reveal intrinsic properties in the data and understand shortcomings in the models that aim to predict the observations.

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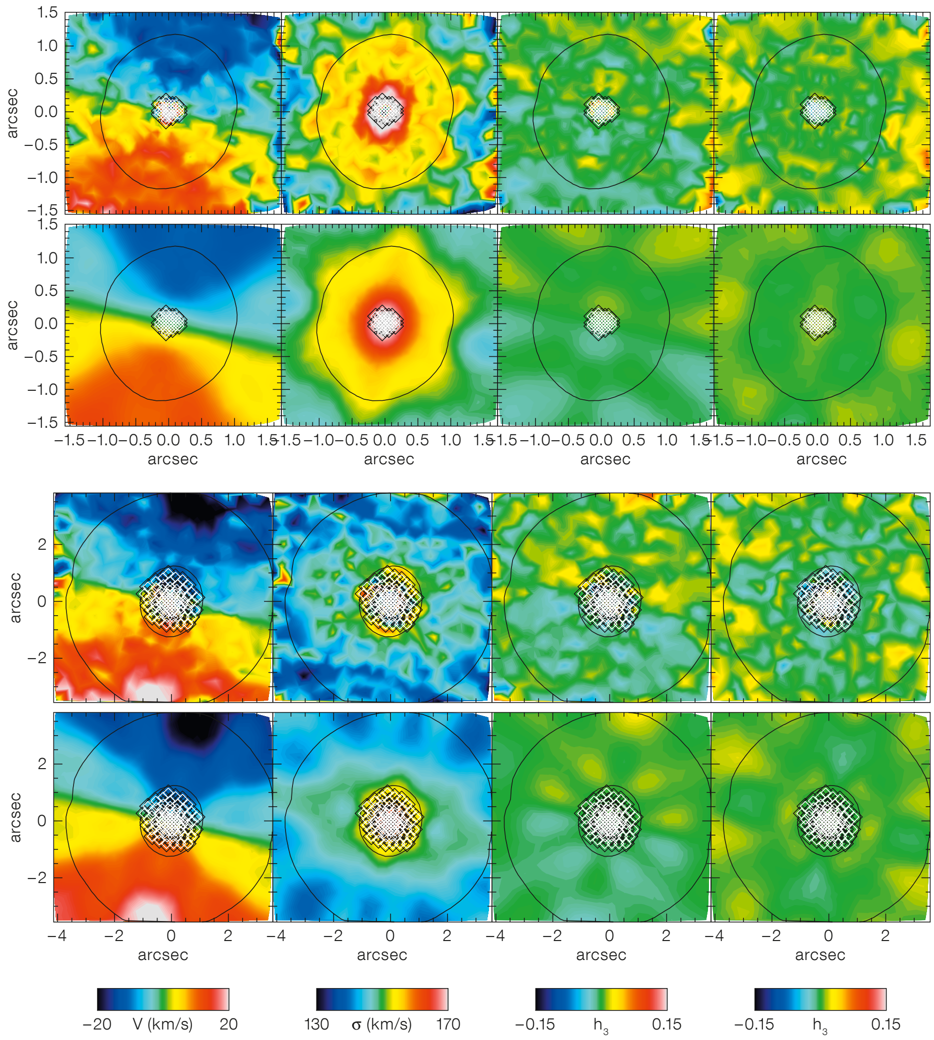

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Figure 5 (left). Data-model comparison for the best-fitting three-integral model. Top two panels: the top row shows the bisymmetrised and linearly interpolated 100-milliarcsecond SINFONI data. The second row shows the best-fitting dynamical model predictions. The central bins that were excluded from the fit are shown with the white diamonds. Bottom two panels: same as in the top two panels, for the 250-milliarcsecond SINFONI kinematics. For each quantity, the colour scale is the same in the two instrumental configurations.

Figure 6 (below). Cen A's black hole mass measurements are plotted on the two black hole mass–galaxy scaling relations. The left panel shows the M_{BH}–σ relation reproduced after Tremaine et al. (2002). The right panel shows the the M_{BH}–M_{Bulge} relation as presented in Häring & Rix (2004) with Cen A values over-plotted. The plot symbols are indicated in the upper left corner. Their time sequence is plotted in the upper left corner of the right panel. In the left panel (and for Cen A measurements) triangles refer to gas kinematical measurements, while circles refer to dynamical models using stellar kinematics.