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Black holes in low-mass bulges and pseudobulges

N. Nowak[1,2], R.P. Saglia[1,2], J. Thomas[1,2], P. Erwin[1,2], and R. Bender[1,2]

[1] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, 85748 Garching, Germany, e-mail: nnowak@mpe.mpg.de
[2] Universitäts-Sternwarte, Scheinerstrasse 1, 81679 München, Germany

Abstract. We are investigating whether the well-known relations between the mass of a central supermassive black hole and the mass or velocity dispersion of its surrounding bulge (the $M_{\bullet}$-σ relation) remain valid—or how they change—when galaxies with pseudobulges or low-mass bulges are considered. Possible differences in these relations can tell us about the relative importance of different growing mechanisms. We present the data collected with the adaptive optics assisted near-infrared integral field spectrograph SINFONI at the VLT and show some first results.

Key words. Galaxies: kinematics and dynamics

1. Introduction

It is now well established that all galaxies with a massive bulge component harbour a central supermassive black hole (SMBH). The mass of the SMBH correlates with bulge properties like the bulge mass (the SMBH mass is about 0.15% of the bulge mass) and the velocity dispersion σ. These correlations are poorly constrained at the low-σ end ($\sigma < 120$ km s^{-1}) and at the high-σ end ($\sigma > 300$ km s^{-1}). In addition the validity of these relations are also mostly unclear for galaxies different from normal, quiescent ellipticals or massive classical bulges of spiral galaxies. In contrast to classical bulges, which we believe form through merging, pseudobulges show more disc-like characteristics, both photometrically and kinematically (Kormendy & Kennicutt, Jr. 2004). They are the result of secular evolution (e.g. bar instabilities), which raises the questions if and how this different growing mechanism is related to the SMBH growth and if there is a black hole at all in those bulges. Often bulges cannot be clearly classified as pseudo or classical, because they are compound systems with both a pseudo and a classical component (Erwin et al. 2003; Erwin 2008). These galaxies can also help to disentangle which growing mechanism is more important for the black hole evolution. Other galaxies barely studied are merger remnants. The reason for that is mainly the dust, which hampers optical spectroscopy. Measuring the SMBH mass of galaxies that recently underwent a merger event is important to understand the sequence, coherence and timescales on which SMBHs and their surrounding bulges evolve and thus to constrain present theories of bulge and black hole evolution (e.g. Di Matteo et al. 2005; Hopkins et al. 2008). In the same context it is also important to study the role of AGN activity in bulge and SMBH growth. Dynamical measurements of SMBH masses in

Send offprint requests to: N. Nowak

strong AGN are also crucial to verify the applicability of reverberation mapping measurements, which is presently the only technique that can be used to measure black hole masses at high redshift. Other galaxy types that need further investigation are e.g. core ellipticals and bulgeless galaxies.

In the past, dynamical black hole mass measurements of those galaxy types have been impossible in most cases because of several, often unsurmountable, difficulties of mostly technical nature. (1) The sphere of influence of the black hole is much smaller than 1″ for most nearby low-σ galaxies, most pseudobulges and strong AGN, which are mostly found at larger distances. (2) Measuring stellar kinematics reliably requires a S/N larger than 30. For small, faint bulges and core galaxies with a low surface brightness, this demands very long integration times. (3) Dust obscuration is a problem, that affects late-type galaxies, the class low-σ galaxies and pseudobulges belong to, and merger remnants. (4) In AGN the problem arises, that the non-stellar emission of the active nucleus dilutes the stellar absorption features. With the adaptive-optics assisted near-infrared integral-field spectrograph SINFONI (Eisenhauer et al. 2003; Bonnet et al. 2004) at the VLT it is possible to overcome most of these difficulties for a number of interesting galaxies. It is possible to reach diffraction-limited spatial resolution ($\lesssim 0.1''$), the large light collecting power of the VLT reduces the needed integration time to a fair amount, dust obscuration plays only a minor role in the *K* band, and AGN emission is less prominent in the near-IR. In the following we present SINFONI observations of the centres of low-σ galaxies, pseudobulges, and one merger remnant.

2. Observations and first results

We observed seven pseudobulges, four low-σ galaxies and one merger remnant with SINFONI (see Table 1). For two galaxies with a faint nucleus we made use of the the laser guide star PARSEC (NGC 3368 and NGC 3627), the others were observed in natural guide star mode using either the nucleus or

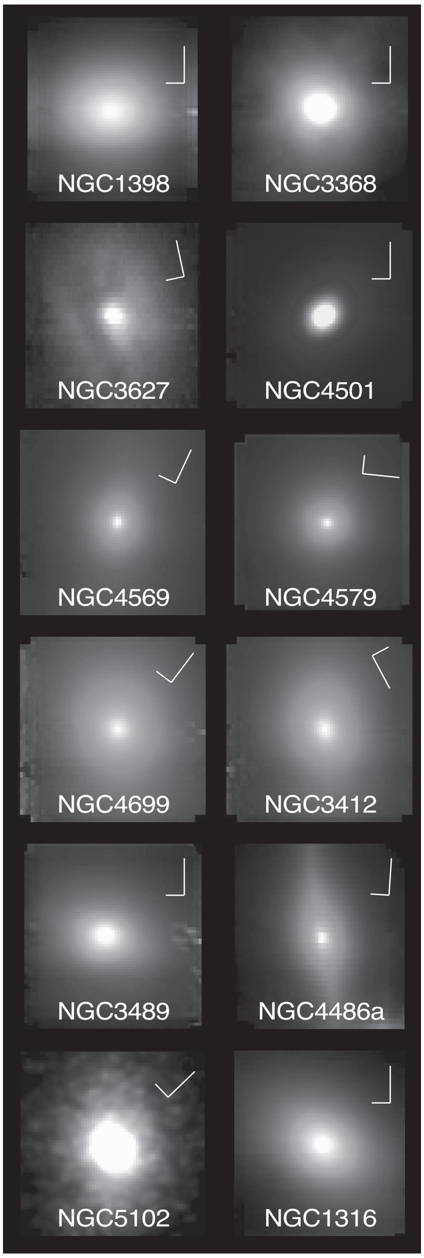

Fig. 1. SINFONI *K* band images of the observed galaxies. The field of view of NGC 3489 is 0.8″, and 3″ for all other galaxies. The orientation is indicated by the small coordinate systems, where north is indicated by the long axis and east by the short axis.

a nearby bright star. Fig. 1 shows the SINFONI images of the observed galaxies. Their nuclei show either no or only weak activity.

The data reduction is done using the SINFONI data reduction package SPRED (Schreiber et al. 2004; Abuter et al. 2006) and the ESO pipeline. All common reduction steps necessary to reduce near-IR data are applied and at the end three-dimensional datacubes are reconstructed. The stellar kinematic information are extracted using the maximum penalized likelihood technique of Gebhardt et al. (2000) from the first two bandheads ^{12}CO(2 − 0) and ^{12}CO(3 − 1) at $\lambda > 2.29\mu$m. To determine the mass of the central SMBH we use the code of Gebhardt et al. (2000, 2003) in the version of Thomas et al. (2004), which assumes axisymmetric galaxies. The code is based on the Schwarzschild (1979) orbit superposition technique. It calculates first the gravitational potential of the galaxy from the stellar mass density, using a trial black hole mass $M_\bullet$ and mass-to-light ratio Υ. The stellar mass density is derived from archival high-resolution HST imaging at the centre and wide field ground-based imaging for the outer parts where available. For this gravitational potential a weighted superposition of orbits is constructed that best matches the observational constraints. This is repeated with different $M_\bullet$ and Υ until the eligible parameter space is systematically sampled. The best-fitting $M_\bullet$ and Υ follow from a χ^2-analysis. The 3D nature of the data has the advantage that we are able to check the assumption of axisymmetry by modelling each of the four galaxy quadrants separately.

2.1. NGC 4486a

The first result of our study is the detection of a SMBH in the low-luminosity elliptical galaxy NGC 4486a in the Virgo cluster (Nowak et al. 2007). It contains an almost edge-on nuclear disc of stars and dust. A spatial resolution of $\approx 0.1''$ was achieved by using the bright star $\sim 2.5''$ away from the centre as a natural guide star for adaptive optics. We found a black hole mass $M_\bullet = 1.25^{+0.75}_{-0.79} \times 10^7$ M$_\odot$ (90% C.L.). With a velocity dispersion of 110 km s^{-1}(2″ diameter aperture) this is in perfect agreement with the the $M_\bullet$-σ relation of Tremaine et al. (2002).

2.2. Fornax A

Fornax A (NGC 1316) is a prominent merger remnant with giant radio lobes located in the outskirts of the Fornax galaxy cluster. So far a measurement of the SMBH mass has not been possible due to the large amounts of dust. In the *K* band the influence of dust is negligible in the central $\sim 3''$. With SINFONI we achieved a spatial resolution of $\sim 0.085''$, which is about a fifth of the diameter of the expected sphere of influence of the black hole. Fornax A does not rotate inside the inner $\sim 3''$. The velocity dispersion increases towards the centre. The weak AGN emission affects the stellar kinematics in the inner $\sim 0.06''$ only. Beyond this radius, the stellar kinematics appears relaxed in the central regions. We find $M_\bullet = 1.5^{+0.75}_{-0.8} \times 10^8$ M$_\odot$ when folding and averaging the data into one quadrant. Similar black hole masses are obtained when modelling the individual quadrants separately, confirming the validity of our assumption of axial symmetry (Nowak et al. 2008). With a velocity dispersion of 226 km s^{-1}(8″ diameter aperture) Fornax A appears close to the $M_\bullet$-σ relation of quiescent galaxies.

3. Summary and outlook

The data reduction, analysis and dynamical modelling for the remaining galaxies is under way. In the present stage of our study no deviation from the $M_\bullet$-σ relation for any of the studied galaxy types (low-σ and merger) is found, but we will only be able to draw final conclusions after having analysed all observed galaxies. Future SINFONI observations will focus on the high-σ ($\sigma > 300$ km s^{-1}) end and core ellipticals. Apart from the SMBH mass and thus the implications on theories of bulge and black hole formation we can extract other interesting information from our SINFONI data. The high-resolution 3D data are a valuable source to study the kinematics of pseudobulges with unprecedented accuracy. The origin, distribution and kinematics of gas (e.g. H_2) can

Table 1. Distance D, velocity dispersion σ, diameter of the sphere of influence d_{soi}, achieved spatial resolution and galaxy type for the galaxies observed with SINFONI.

Galaxy	D (Mpc)	σ (km s^{-1})	d_{soi} ($''$)	resolution	type
NGC 1398	18	200	0.34	0.19	pseudo
NGC 3368	10	128	0.22	0.15	pseudo
NGC 3627	10	115	0.19	0.088	pseudo
NGC 4501	13	161	0.33	0.13	pseudo
NGC 4569	16	117	0.11	0.15	pseudo
NGC 4579	16	154	0.23	0.15	pseudo
NGC 4699	19	215	0.37	0.13	pseudo
NGC 3412	11	101	0.11	0.13	low-σ
NGC 3489	12	100	0.12	0.08	low-σ
NGC 4486a	16	110	0.13	0.10	low-σ
NGC 5102	4	65	0.10	0.07	low-σ
NGC 1316	18	226	0.44	0.085	merger

also be analysed in detail. Increasing attention is presently drawn to the measurement and interpretation of near-IR line indices (Silva et al. 2008; Mármol-Queraltó et al. 2008). For our SINFONI data we are able to measure two-dimensional K band line index maps and therefore can trace variations in the stellar populations in the central parts of galaxies.

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