A high-angular resolution study of the nuclear regions of quasar host galaxies with the NaCo Simultaneous Differential Imager

J Scharwächter1, V D Ivanov1, J Zuther2, L E Tacconi-Garman3, J K Kotilainen1 and J Reunanen4

1 European Southern Observatory, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile
2 Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße 1, D-85748 Garching bei München, Germany
3 European Southern Observatory, Karl-Schwarzschild-Straße 2, D-85748 Garching bei München, Germany
4 Tuorla Observatory, University of Turku, Väisäläntie 20, FIN-21500 Piikkiö, Finland

E-mail: jscharwa@eso.org

Abstract. A project aiming at the study of the emission line gas morphology in quasar host galaxies by means of adaptive-optics-assisted simultaneous narrow-band imaging of the line and continuum emission is presented. The project makes use of the NaCo Simultaneous Differential Imager (SDI) in an extragalactic experiment. The quasar targets are selected according to the availability of a neighbouring natural guide star for adaptive optics (AO) correction and according to a redshift criterion which places one of the emission lines of Paβ, Hα, or [O iii] into one of the three SDI narrow-band filters in the near-infrared H-band. The first results for six targets from the Sloan Digital Sky Survey (SDSS) Quasar Catalogue at redshifts of about 0.2, 1.4, and 2.1 are summarized. The strongest line emission is detected for the Hα candidate SDSS J125100.42+033726.5 at a redshift of 1.386. A double-structured continuum source is found in the central region of SDSS J114203.40+05135.8, which might be correlated with the major merger process suggested by the one-armed tidal tail in the large scale morphology.

1. Introduction

Emission line gas around quasars can be used as a tracer of the gas morphology in the quasar host galaxies. The typical mechanisms producing emission lines are ionisation by hot stars, by the AGN, or by shocks [see e.g. 31]. At low redshift (z < 0.5), extended emission line regions (EELR) with [O iii] emission on scales of a few tens of kiloparsecs are found around many steep-spectrum radio-loud quasars [e.g. 1-5]. But there is also evidence for similar emission line regions around radio-quiet quasars [6]. Possible scenarios for the various types of these EELRs include associations with radio jets and lobes, with superwinds, or with tidal interactions [4, 5, 6]. High angular resolution, as provided by AO techniques, is essential for studying the morphology of emission line gas close to the bright quasar nucleus. However, imaging-based studies using an

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Figure 1. Observed wavelength of the Paβ line for three example redshifts of the targets of this study (arrows). The three NaCo SDI narrow-band filters are schematically shown as dashed boxes with widths of 0.025 µm, corresponding to the FWHM of the filters (see [26], Fig. 2, for the detailed filter curves). The red spectrum represents the template of G2V stars (from [27]) which are used for relative flux calibration purposes.

AO system are rare. The authors of [7] observed a sample of five quasars at redshifts of 0.9 to 2.4 using an AO system and narrow-band filters covering the [O iii] and Hα emission. All of the five targets, which are radio-quiet or very compact radio sources, show line emission within a few kiloparsecs of the nucleus, i.e. on more compact scales than the EELRs [1-5] mentioned above. It is speculated by the authors of [7] that the Hα emission, where detected, indicates young stars. An exception is the jet-like Hα feature in one case which rather indicates nuclear beaming. The [O iii] detections typically show a radial linear morphology, which aligns with the radio structure where the latter is resolved. This suggests nuclear beaming [7].

NaCo (NAOS-CONICA), [8, 9], is the Nasmyth Adaptive Optics System NAOS together with the 1 µm - 5 µm imager and spectrograph CONICA installed at UT4 of the ESO Very Large Telescope (VLT) on Cerro Paranal. The NaCo Simultaneous Differential Imager (SDI), [10, 11], is designed for high-contrast imaging. It provides four simultaneous images through three different narrow-band filters in the near-infrared $H$-band. Each of the four simultaneous images has a field-of-view of about 5′′ × 5′′. The pixel scale of the SDI camera is 17.32 mas. The four beams are produced by directing the incoming beam through two consecutive Wollaston prisms which are rotated by 45 deg with respect to each other. Two of the resulting images are centred at 1.625 µm, which is inside the methane absorption typical of cool brown dwarfs and gas giants [e.g. 11]. The two remaining images are centred on the nearby continuum at 1.575 µm and 1.600 µm, respectively. The main science case of the instrument is the detection of methane-rich companions close to bright stars. High-contrast images of such companions can be achieved by subtracting out the bright star, the speckle pattern of which is very similar in the four simultaneous images [e.g. 12].

The data discussed here are the first results from a project in which the NaCo SDI together with AO is used for an extragalactic experiment aiming at a study of the emission line gas
morphology in quasar host galaxies. The quasar candidates are selected via a redshift criterion which places one of the major gas emission lines into one of the SDI narrow-band filters (Fig. 1). The redshift bins corresponding to the typical emission lines of Paβ, Hα, or [O iii] are \( z \sim 0.2 \), \( z \sim 1.4 \), and \( z \sim 2.1 \), respectively. The project takes advantage of the similar quasar point-spread functions in the simultaneous line and continuum images when subtracting the continuum of the quasar nucleus.

The final sample of quasar candidates is constrained by the requirement of a suitable guide star for AO correction and by the restriction to certain redshift bins. A total of six quasars from the SDSS Quasar Catalogue [13] and two quasars from the Hamburg/ESO survey [30, and references therein] have been observed so far. The analysis of the data for the two quasars from the Hamburg/ESO survey, observed during a follow-up programme in February and March 2008, is ongoing. Thus, only the data for the six SDSS sources are presented here. The data and the basic reduction methods are described in Section 2. An overview over the first results with special focus on SDSS J125400.42+033726.5 and SDSS J114203.40+005135.8 is given in Section 3. A brief summary is presented in Section 4.

2. Observations and data reduction

The six sources from the SDSS Quasar Catalogue [13] were observed during two nights in April 2006. SDSS J114203.40+005135.8 was re-observed during the follow-up programme in February/March 2008. The separations between the six SDSS sources and their guide stars range from 10′′ to 33′′ and the guide star V-band magnitudes are in the range of 12 to 15 mag. Consequently, the AO corrections provide moderate Strehl ratios of a few percent at most. In addition, the second observing night in April was affected by unfavourable seeing conditions. All observations were done with a small jitter on the target and with regular offsets to an empty sky field.

The data are reduced using standard near-infrared reduction steps with some adaptations to the particular characteristics of the NaCo SDI data. After cosmic ray removal following the method of [28], the data are sky-subtracted. Each of the four simultaneous images is flat-fielded and corrected for bad pixels individually. The signal-to-noise ratio in the individual images for most of the SDSS targets is too low to use the target positions themselves for registering the jittered frames. In order to increase the signals of the targets, the four simultaneous images at one jitter position are combined first. This step makes use of the fixed relative offsets between the four simultaneous images on the detector, which are determined from the data for the bright standard stars. The combined images with the highest object signal are selected and registered via cross-correlation. In the case of fainter sources, the combined images are smoothed with a Gaussian convolution first. The offsets resulting from the cross-correlation method are retroactively used to register each of the four simultaneous images individually and to combine all frames per image. In order to correct for the small differences in the radial extension of the point-spread functions at the slightly different wavelengths of the three narrow-band filters, the coadded images are rescaled in pixel size.

The relative flux calibration between the four simultaneous images is derived from images of G2V standard stars in comparison to the integrated \( H \)-band spectrum of the sun [29]. Since the NaCo SDI consists of two Wollaston prisms, polarisation effects might play a role. However, for Wollaston prisms with ideal transmission characteristics two pairs of the final four images should show the same intensity. Assuming that the standard stars are unpolarised, the relative flux calibration should not be affected by polarisation. Any significant contamination of the emission line detections by polarised light from the quasars should become evident as a strong flux residual in the differences between the continuum images.
Table 1. Summary of the observed quasars and first results.

| Target                  | Redshift | Emission Line | First Results                   |
|-------------------------|----------|---------------|---------------------------------|
| SDSS J162343.13-003324.1| 0.223    | Pa_β          | Weak sign of line emission      |
| SDSS J114203.40+005135.8| 0.245    | Pa_β          | Double structured continuum     |
| SDSS J151412.58-000311.8| 0.228    | Pa_β          | Possible sign of line emission  |
| SDSS J125400.42+033726.5| 1.386    | H_α           | Line emission                   |
| SDSS J100813.58-000218.6| 1.478    | H_α           | Not detected                    |
| SDSS J205550.46-055740.4| 2.153    | [O III]       | Weak sign of continuum emission |

Figure 2. Comparison of the four NaCo SDI images through the three different narrow-band filters for SDSS J125400.42+033726.5. The contour levels in all four images are the same and show 3σ to 8σ steps based on the maximum of the four standard deviations of the sky backgrounds. All images are displayed with the same scaling. The images are smoothed by a Gaussian with a sigma of 17.32 mas and are composed of frames with a total integration time of 1200 s. 0.5 arcsec corresponds to 4.2 kpc at the source redshift^2.

3. Results

The six SDSS sources observed for this project and the first results are briefly summarized in Table 1. Two of the targets – SDSS J125400.42+033726.5 and SDSS J114203.40+005135.8 – are selected for a more detailed discussion. SDSS J125400.42+033726.5 shows the strongest evidence for a putative detection of emission line gas among the six candidates. The continuum image of SDSS J114203.40+005135.8 reveals a double-structured nuclear source at high angular resolution.
Figure 3. Hα (plus [N ii]) image of SDSS J125400.42+033726.5 (upper left panel) based on the four reduced images shown in Fig. 2. The upper left panel shows the average of the two differences between the 1.575 μm filter (Hα plus [N ii]) and the two continuum images at 1.625 μm. The other panels show the differences between the remaining three SDI images, as indicated in the titles. 1.625_left/right refers to the two images taken through the 1.625 μm filter which are displayed in the lower left and right panels of Fig. 2, respectively. The scaling in all four images is the same.

3.1. SDSS J125400.42+033726.5: Hα candidate at z = 1.386

SDSS J125400.42+033726.5 with an SDSS r-band magnitude of 18.82 mag [13] is basically unstudied in the literature and has no spectral classification. There is no associated X-ray or radio source in the X-ray and radio catalogues investigated in [14].

The first results for SDSS J125400.42+033726.5 are shown in Figs 2 and 3. These are based on data taken at an airmass of about 1.2 and under zenith seeing conditions of about 1″ at 0.5 μm (i.e. about 0″8 at 1.6 μm). The measured full width at half maximum (FWHM) of the nuclear source of SDSS J125400.42+033726.5 in the continuum images in Fig. 2 is about 0′′15, i.e. 1.3 kpc (1″ ≈ 8.4 kpc at the source redshift\(^2\)).

The composite of the four reduced NaCo SDI images (Fig. 2) indicates excess emission in the 1.575 μm filter at a ∼ 7σ level with respect to the standard deviation of the background. At the redshift of SDSS J125400.42+033726.5, this excess emission is attributable to Hα (plus [N ii]) emission shifted to the short-wavelength edge of the 1.575 μm filter. [S ii] emission redwards of Hα is shifted into the 1.600 μm filter which, however, shows no clear evidence of line emission. The residual Hα (plus [N ii]) emission after continuum subtraction is shown in Fig. 3. Strong systematic effects from the relative flux scaling of the four SDI images or from polarisation can be excluded based on the difference images for the 1.600 μm and 1.625 μm filters in Fig. 3. Besides artefacts in the background, the latter show low-level flux residuals at the position of the source which are also evident as an uncertainty in the source morphology and

\(^2\) calculated for \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \text{ and } \Omega_\Lambda = 0.7\) using the online cosmology calculator of [32]
Figure 4. SDSS J114203.40+005135.8 and the AO guide star in an averaged J- and H-band image from the ISAAC (VLT) data set presented in [19]. The approximate field of view of the NaCo SDI image shown in Fig. 5 is indicated by the white box. 10″ corresponds to 39 kpc at the source redshift squared.

Figure 5. NaCo SDI image of the double-structured nuclear continuum of SDSS J114203.40+005135.8. The image displays a median-combination of the four simultaneous images (integration time of 2100 s) after smoothing by a Gaussian convolution with a sigma of 17.32 mas. These new data from March 2008 show higher quality than the previous data presented in [19]. 0″5 corresponds to 1.9 kpc at the source redshift squared.

Signal in the 1.600 μm and 1.625 μm contour images (Fig. 2). Owing to these uncertainties in the continuum images, the exact morphology and signal level of the Hα (plus [N II]) detection is not yet fully reliable. Further investigation is needed to understand the origin of the variations in the continuum images before radial and/or two-dimensional modelling of the putative detection of emission line gas in SDSS J125400.42+033726.5.

3.2. SDSS J114203.40+005135.8: Double-structured continuum

Among the six SDSS objects, SDSS J114203.40+005135.8 is the best studied source. There are, however, no publications referring to SDSS J114203.40+005135.8 on a more individual basis. It is included in several catalogues and publications about larger samples. The SDSS r-band magnitude of SDSS J114203.40+005135.8 is 18.47 mag [13]. The classification of this source is rather controversial. In the different catalogues it is classified as a quasar [13], a Seyfert 1 galaxy [15], a LINER [16], and an ultra-luminous infrared galaxy [17]. It is a radio source with 17.68 mJy at 1.4 GHz and shows spectral characteristics of star formation activity [18].

The new NaCo SDI image of SDSS J114203.40+005135.8 is presented in Fig. 5. It is based on data which were obtained at an airmass of about 1.1 and under zenith seeing conditions of about 0″9 at 0.5 μm (i.e. about 0″7 at 1.6 μm). The continuum emission reveals a double-structured nuclear source. This nuclear double structure was first reported in [19]. It is confirmed by the new NaCo SDI observations from March 2008. The two luminosity peaks are separated by about 0″7, i.e. 2.7 kpc (1″ ≈ 3.9 kpc for SDSS J114203.40+005135.8 squared). At the redshift of z = 0.245, the Paβ emission falls into the 1.600 μm filter. Based on the first reduction results presented here, the differences between the 1.600 μm image and the nearby narrow-band images do not reveal a clear sign of Paβ emission. This might possibly be caused by contamination from [Fe II]
in the 1.575 μm image and from O I in the 1.625 μm image.

The large-scale morphology of SDSS J114203.40+005135.8 with the pronounced one-armed tidal tail (Fig. 4) and the double luminosity peak in the nuclear region are reminiscent of the radio-loud quasar 3C 48 [see also 19]. In the case of 3C 48, the second luminosity peak close to the quasar nucleus has been a matter of controversy [20-25, 33]; It could originate from an interaction of the radio jet with the interstellar medium, or represent a second galaxy in the late stage of a merger with 3C 48. Recent evidence is in favour of the merger scenario and suggests an evolutionary phase in which the quasar activity is young and the merger process – as the likely cause of the quasar activity – is witnessed before the final coalescence of the two galaxy centres [25]. A priori, the same two scenarios as for the two luminosity peaks in 3C 48 could be invoked to explain the double-structured continuum in the centre of SDSS J114203.40+005135.8. It is unknown whether the radio source in SDSS J114203.40+005135.8 is associated with a jet which could be responsible for the observed structure. Alternatively, multi-particle simulations for 3C 48 suggest that a major merger process producing a one-armed tidal tail structure via projection effects is not in contradiction to a merger stage in which the two galaxy centres are still separated [24]. In this respect, SDSS J114203.40+005135.8 might be another example of a young phase in quasar evolution.

4. Summary
The first results for a sample of six sources from the SDSS Quasar Catalogue [13] observed with the NaCo SDI with the aim to study the emission line gas morphology via simultaneous differential imaging in the near-infrared $H$-band are presented. Two remarkable objects from the first analysis are discussed in more detail: (i) SDSS J125400.42+033726.5 shows an evident excess emission in the SDI filter at 1.575 μm, likely due to Hα (plus [N II]) emission. The emission line image for this source will be the subject of a deeper investigation via radial and 2D modelling. (ii) SDSS J114203.40+005135.8 reveals a nuclear double-structured continuum at high angular resolution with an improved signal-to-noise ratio with respect to the previous data set presented in [19]. This source with a controversial classification in the literature shows similarities to 3C 48 and could be in an early phase of quasar evolution.

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