Abstract

We report on ESO–VLT adaptive optics imaging of one radio-loud quasar at $z \sim 3$. In spite of the large distance of the object we are able to detect its surrounding extended nebulosity the properties of which are consistent with an underlying massive galaxy of $M_K \sim -27$ and effective radius $R_e = 7$ kpc. As far as we know this is the clearest detection of a radio loud quasar host at high redshift. The host luminosity is indicative of the existence of massive spheroids even at this early cosmic epoch. The host luminosity is about 1 magnitude fainter than the expected value based on the average trend of the host galaxies of RLQ at lower redshift. The result, which however is based on a single object, suggests that at $z \sim 3$ there is a deviation from a luminosity–redshift dependence regulated only by passive evolution.

Key words: galaxies: active, galaxies: evolution Quasars: general
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1 Introduction

It is well known that at low redshift quasars are hosted in otherwise normal luminous (and massive) galaxies (Bahcall et al., 1997; Dunlop et al., 2003; Pagani et al., 2003) characterized by a conspicuous spheroidal component that becomes dominant in radio loud objects (RLQ). These galaxies appear to follow the same relationship between the bulge luminosity and the mass of the central black hole observed in nearby inactive elliptical galaxies (Ferrarese, 2002). If this link keeps also at higher redshift the observed population of
high $z$ quasars traces the existence of $\sim 10^9 \, M_\odot$ super massive BHs and massive spheroids at very early ($< 1$ Gyr) cosmic epochs (Fan et al., 2001, 2003; Willott, McLure & Jarvis, 2003).

Indeed this idea seems also supported by the discovery of molecular gas and metals in high $z$ quasars (Bertoldi et al., 2003; Freudling, Corbin & Korista 2003), that are suggestive of galaxies with strong star formation. In this context it is therefore important to push as far as possible in redshift the direct detection and characterization of QSO host galaxies. In particular, a key point is to probe the QSO host properties at epochs close to (and possibly beyond) the peak of quasar activity ($z \sim 2.5$).

Till few years ago, due to the severe observational difficulty, the properties of quasar hosts at high redshift were very poorly known (e.g. see the pioneering papers by Hutchings (1995); Lehnert et al. (1992); Lowenthal et al. (1995). Uncertain or ambiguous results, were produced because based on inadequate quality of the images (modest resolution; low S/N data; non optimal analysis).

In this work we present first results of a program aimed at imaging the host galaxies of quasar at $z > 2$ using adaptive optics at 8m class telescopes. Throughout this work we use $H_0 = 70\, \text{km s}^{-1}\, \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_L = 0.7$.

2 Adaptive optics imaging of distant QSO

In order to characterize the properties of high $z$ quasar hosts it is of fundamental importance to combine high spatial resolution (narrow PSF) with very good sensitivity to detect and measure the faint nebulosity surrounding the bright QSO nuclei. Adaptive optics (AO) opened a new window in this field, though the first generation of AO systems at 4m class telescopes enabled the detection of details on the host at low $z$ they did not allow much improvements for distant quasars (Hutchings et al., 1998, 1999; Marquez et al., 2001; Lacy et al., 2002).

It was the recent introduction of sophisticated AO systems at 8m class telescopes that, for the first time, provided the spatial resolution and the adequate sensitivity for pushing the detection of QSO hosts at $z \geq 2$, and it did not take long for new results to appear in the literature. Croom et al. (2004) using the AO system at the Gemini North telescope were able to resolve and characterize one radio quiet quasar (RQQ) at $z=1.93$, finding for the host an absolute magnitude of $M_K = -27.3$. In a pilot program at the ESO VLT equipped with the AO system (NACO), Falomo et al. (2005) resolved a radio loud quasar at $z \sim 2.5$. The absolute magnitude of the host was found $M_K = -27.6$. In both
cases the host galaxy luminosity appears to be consistent with the trend followed at lower redshift (Falomo et al., 2004; Kotilainen et al., 2005). RQQ and RLQ host luminosity–redshift dependence follows that of massive spheroids undergoing simple passive evolution. Up to $z \sim 2$ the average host luminosity is about $4L^*$ for RLQ and 0.7 mag fainter for RQQ.

In order to investigate the properties of quasar hosts at $z > 2.5$ and to explore the region near the peak of QSO activity we have carried out a new program to secure K band images of quasars in the redshift range $2 < z < 3$ using the AO system at ESO VLT.

3 Object selection, observations and data analysis

Adaptive optics systems employing natural guide stars imply that only the targets that are sufficiently close to relatively bright stars (used as reference for AO correction) can be actually observed. In order to find an adequate number of targets for AO observations we searched the Veron & Cetty-Veron (2003) catalog of quasars to collect suitable objects in the redshift range $2 < z < 3$ and $\delta < 0$, for sources having a star brighter than $V=14$ within 30 arcsec. Under these conditions the system is expected to deliver images of Strehl ratio better than $\sim 0.2$ when the seeing is $<0.6$ arcsec. Among these candidates we also searched for objects that have other stars in the field usable to derive the PSF. This produced a list of twenty objects only three of which are radio loud. Here we present the results for one RLQ at $z \sim 3$: WGA J0633.1-2333 ($B = 21.5$ ; $z = 2.928$, Perlman et al. 1998).

Two K-band images were obtained using NAOS – CONICA (Rousset et al., 2002; Lenzen et al., 1998), the AO system on the VLT at the European Southern Observatory (ESO) in Paranal (Chile). The detector used (Aladdin InSb 1024x1024 pixels) provides a field of view of 56x56 arcsec with a sampling of 54 mas/pixel. The object was observed using a jitter procedure and individual exposures of 2 minutes per frame, for a total integration time of 48 minutes (see Figure 1).

4 Results

We performed a detailed modeling of the image of the object using a new software specifically designed to perform two dimensional model fitting of QSO images AIDA – Astronomical Image Decomposition and Analysis (Uslenghi & Falomo, 2005). The most critical part of the analysis is the determination of the PSF model and the choice of the background level (that affects the faintest external
signal from the object). In the observed field (see Figure 1) of this QSO we were able to use many stars to characterize the PSF model. The fit of the target was obtained, assuming a combination of a point source and an elliptical galaxy convolved with the proper PSF. The radial brightness profile of the quasar compared with that of the PSF is shown in Figure 1.

The result of the best fit indicates that the host galaxy is a luminous elliptical: K=19.1 ± 0.3 corresponding to M<sub>K</sub> = -27.1 and an effective radius Re ∼ 7 kpc.

![Fig. 1. Left: The K-band image of the radio loud quasar (z = 2.928) WGA J0633.1-2333. Right: The radial brightness profiles (filled squares), superimposed to the fitted model (solid line) consisting of the PSF (dotted line) and an elliptical galaxy convolved with its PSF (dashed line). The image decomposition was performed by AIDA (see text). The associated errors are a combination of the statistical photometry in each bin and of the uncertainty on the background level.](image)
This new measurement, together with the available data on quasar hosts at lower redshift, are reported in Figure 2, which shows that up to $z \sim 2.5$, RLQ appear hosted by massive fully formed galaxies that are undergoing passive evolution. The indication is that at least up to $z=2.5$ there is no decrease in mass (luminosity) as would be expected in the hierarchical merging scenario for the formation and evolution of massive spheroidal galaxies ([Kauffmann & Haehnelt, 2000]).

On the other hand the host galaxy of the RLQ at $z \sim 3$ is fainter by about a factor of 2 with respect to the (average) value that is expected if the RLQ hosts luminosity trend depicted at lower $z$ continues also at higher redshift. This may be suggestive of a real drop in luminosity and likely also in mass of the hosts of the quasars. This downturn in luminosity, that appears to occur very close to the epoch where there is the peak of QSO activity, if confirmed, thus indicates a very early epoch for the last major merger of galaxies and emphasizes a strict QSO-host co-evolution.

Because of the potential cosmological importance of the result in the context of the models of galaxy and BH formation it is mandatory to resolve a sizeable number of objects at $z \sim 3$ and beyond. We have an ongoing program at VLT to explore the quasar host properties of a sizeable sample of $z > 2$ objects.

References

Bahcall, J.N., Kirhakos S., Saxe D.H., Schneider D.P. 1997, ApJ 479, 642
Bertoldi F., Carilli C.L., Cox P., et al. 2003b A&A 406, L55
Bressan, A., Granato G.L. & Silva L. 1998, A&A 332, 135.
Croom S.M., Schade D., Boyle B.J., Shanks T., Miller L., Smith R.J. 2004 ApJ 606 126
Dunlop, J.S., McLure, R.J., Kukula, M.J., Baum, S.A., O’Dea C.P., Hughes, D.H. 2003, MNRAS, 340, 1095
Falomo, R. Kotilainen, J.K., Pagani, C. Scarpa R. & Treves A. 2004, ApJ 604 495
Falomo, R. Kotilainen, J.K., Scarpa R. & Treves A. 2005, AA 434 469
Fan X. et al. 2001, AJ, 121, 54
Fan X. et al. 2003, AJ, 125, 1649
Ferrarese, L., 2002, Proceedings of the 2nd KIAS Astrophysics Workshop, (ed. C.-H.Lee, H.-Y.Chang) Singapore: World Scientific Publishing, p.3
Freudling W., Corbin M.R., & Korista K.T. 2003 ApJ 587, 67
Hutchings, J. B. 1995 AJ, 110, 994
Hutchings J.B. Crampton D., Morris S.L., Steinbring E. 1998 PASP 110 374
Fig. 2. The evolution of radio loud quasar host luminosity compared with that expected for massive ellipticals (at $M^*$, $M^*-1$ and $M^*-2$; solid, dotted and dashed line ) undergoing passive stellar evolution (Bressan Granato & Silva 1998). The host galaxy of two RLQ at $z \sim 2.5$ and 2.9 is compared with the data for samples of lower redshift RLQ presented in Falomo et al. (2004). Each point is plotted at the mean redshift of the considered sample while the error bar represents the 1σ dispersion of the mean except for the individual objects at $z > 2$ where the uncertainty of the measurement is given.

Hutchings J.B., Crampton D., Morris S.L., Durand D., Steinbring E., 1999 AJ 117, 1109
Kauffmann, G., Haehnelt, M., 2000, MNRAS, 311, 576
Kotilainen, J.K., Falomo, R. Scarpa, R. Treves & Uslenghi, M. 2005, this conference
Lacy M., Gates, E.L. Ridgway, S.E., de Vries W. Canalizo G., Lloyd, J.P., Graham, J. R. 2002 AJ 124 3023
Lehnert, M.D., Heckman, T.M., Chambers, K.C., Miley, G.K. 1992 ApJ, 393, 68
Lenzen R., Hofmann R., Bizenberger P., Tusche, A., 1998, Proc. SPIE, 3354, 606
Lowenthal, J.D., Heckman, T.M., Lehnert, M.D., Elias, J.H. 1995 ApJ, 439, 588
Marquez I., Petitjean P., Thodore B., Bremer M., Monnet G., Beuzit J.-L. 2001 AA 371 97
Pagani, C., Falomo, R., Treves, A., 2003, ApJ 596, 830
Perlman E., Padovani, P. Giommi P. et al. 1998AJ 115 125.
Rousset, G., Lacombe, F., Puget, P., Gendron, E., Arsenault, R., et al., 2000, Proc. SPIE, 4007, 72
M.Uslenghi & R.Falomo, 2005 in preparation
Veron-Cetty M.P., Veron P. 2003, A&A, 412, 399
Willott C.J., McLure R.J. & Jarvis M.J. 2003 ApJ 587, L15
Winn, J.N., et al. 2003, ApJ 697, 672.