Resolving the Host Galaxies of Quasars at $z = 2.5$ with VLT + NACO

Based on the most widely accepted model for structure formation in the universe, the massive galaxies we see today are the result of the merging of smaller structures. Looking far enough, and therefore far back in time, one should then be able to see galaxies getting smaller and smaller. To explore this issue we focus on quasars host galaxies and trace their properties up to redshift $z = 2.5$ (about 8 billion years in the past). Observations indicate that up to $z \sim 2.5$ quasar hosts are massive galaxies that are fully formed even at these early epochs. This is in partial disagreement with the hierarchical merging scenario, for the formation of massive spheroids.

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Ground-based imaging together with higher-resolution Hubble Space Telescope data show that in the local universe ($z < 0.5$) powerful quasars (QSO) are found in massive elliptical galaxies. At higher redshift (up to $z \sim 2$) the available data confirm this scenario (Falomo et al. 2004, and reference therein), in particular indicating that the luminosity of QSO host galaxies is consistent with that of massive spheroids undergoing passive evolution.

For $z > 2$ the properties of the hosts are very poorly known because of the severe difficulties of getting direct information on these galaxies. There are, however, some indirect arguments supporting the above scenario. The Sloan Digital Sky Survey has observed hundreds of high-redshift QSO sufficient to constraint their space density up to $z \sim 6$ (e.g., Fan et al. 2003). These objects trace the existence of ~ 109 solar masses super-massive BHs (Willott et al. 2003). If the proportionality observed in the local universe between the BH mass and the hosting spheroid holds also at these epochs, then one could argue that massive host galaxies are already formed at these redshifts. Furthermore, even in the highest-redshift objects known, evidence has been found for the existence of molecular gas (Walter et al. 2004), dust (Bertoldi et al. 2003), and metals (Freudling et al. 2003), indicating that even at these early epochs QSO are associated with galaxies that have experienced significant star formation.

These observations appear at odds with the widely accepted Λ cold dark matter cosmologies, which predict a significant drop in mass of high z galaxies as a consequence of the processes of hierarchical merging (e.g., Kauffmann et al. 2000).

In this context, it is 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 properties of the host at epochs close to (and possibly beyond) the peak of quasar activity ($z \sim 2.5$), to verify whether the properties observed at lower redshift, like the central black hole – bulge mass relation, hold even at these early epochs. This is not attainable either with HST or 4-m-class telescopes equipped with adaptive optics (AO) systems because of the modest aperture that translates into a limited capability to detect faint extended nebulosity. One thus has to resort to 10-m-class telescopes equipped with AO systems to reach the required spatial resolution and depth. For instance, in a recent study by Croom et al. (2004) of nine $z \sim 2$ quasars imaged with AO at Gemini North telescope, one source at $z = 1.93$ was resolved. No quasars at $z > 2$ have been till now clearly resolved using AO imaging systems, though some claim in this sense has been made (Kuhlbrodt et al. 2005).

Here we present the first results of a pilot programme aimed to secure near-IR (K-band) images of quasars in the redshift range $2 < z < 3$, using the AO system at VLT. As we shall show, observations allow us to pin down the host galaxy-luminosity at very early cosmic epochs. The comparison with the results obtained at lower redshift then puts some constraints on the models for galaxy evolution and for the joint formation of galaxies and their central supermassive black hole. The results presented here (a full account of which is given in Falomo et al. 2005) refer to the first run of observations, during which images of three QSO were obtained.

We focus here on the radio-loud quasar PKS 0113-283 located at $z = 2.555$ (Hook et al. 2003). Observations were obtained using NAOS-CONICA, the first Adaptive Optics System on the VLT. We used the S54 camera that provides a field of view of 56 x 56 arcsec with a sampling of 54 mas/pixel. A jitter procedure was followed, with individual exposures of 2 minutes per frame and total integration time of 38 minutes. In the final image a spatial resolution of 0.22 arcsec was achieved (Figure 1). Photometric calibration, performed using standard stars observed during the same night, yields an internal accuracy of ~ 0.1 mag. A star at approximately the same angular distance (16.3 arcsec) from the AO guide star as the target (which is at 15 arcsec from the GS) was used to reliably model the Point Spread Function (PSF) of the system, since the shape of the PSF mainly depends on the distance from the AO guide star. Possible 2D asymmetries of the PSF due to differences in the relative positions of the target and the PSF star with respect to the AO guide star have negligible effect when one considers the azimuthally averaged radial profile. The comparison between the radial surface brightness profile of this star with that of the QSO indicates that the target is resolved (Figure 2). The radial profile was then fitted with a combination of a point source and an elliptical galaxy convolved with the proper PSF.

The result of the fit indicates that the host galaxy is a luminous giant elliptical with apparent magnitude K = 19.1 ± 0.3, corresponding to an absolute magnitude $M_K = -27.6$ (including K-correction, $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$), and an effective radius $R_e = 7.5 \pm 3$ kpc.

Assuming 1 mag of evolutionary effects this correspond to a present epoch magnitude of $M_K = -26.6$, fully consistent with the properties of local giant elliptical galaxies (e.g., Pahre 1998).

Our observations demonstrate that when a PSF characterization is possible, it is feasible to directly detect the host galaxy of quasars at redshift $z > 2$. In the case of PKS 0113-283, at $z = 2.555$, it was found that the quasar is hosted by a massive and fully-formed galaxy, with the size and luminosity expected from the trend observed for lower-redshift quasars (see Figure 3). A similar trend is also observed for radio galaxies (Willott 2003). Therefore, up to $z = 2.5$ there is no evidence of the decrease in mass (luminosity) expected in the hierarchical merging scenario for the formation and evolution of spheroidal galaxies. This result is also difficult to reconcile with models for the joint formation and evolution of massive galaxies and their supermassive black holes (e.g., Kauffmann et al. 2000), which predict quasars should be found in progressively less massive galaxies.

More VLT + NACO data have been secured during period 74 to put this result on solid statistical grounds, and possibly push even further in redshift the direct detection of quasars host galaxies, allowing for more and more stringent tests of the current cosmological models for structure formation.

References

Bertoldi, F., Carilli, C. L., Cox, P., et al. 2003a, A&A406, L55
Croom, S. M., Schade, D., Boyle, B. J., Shanks, T., Miller, L., and Smith, R. J. 2004, ApJ 606, 126
Falomo, R., Kotilainen, J. K., Pagani, C., Scarpa, R.,and Treves, A. 2004, ApJ 604, 495
Falomo, R., Kotilainen, J. K., Scarpa, R., and Treves A. 2005, A&A 434, 469
Fan, X., Strauss, M. A., Schneider, D. P., et al. 2003, AJ 125, 1649
Freudling, W., Corbin, M. R., and Korista K. T. 2003 ApJ 587, 67
Hook, M., Shaver, P. A., Jackson, C. A., Wall, J. V., and Kellermann, K. I. 2003, A&A 399, 469
Kauffmann, G. and Haehnelt, M. 2000, MNRAS 311, 576
Kuhlbrodt B., Örndahl E., Wisotzki L., and Jahnke K. 2005, A&A, in press (astro-ph 0503284)
Pahre, M. A., Djorgovski, S .G., and de Carvalho, R. R. 1998, ApJ 116, 1591
Walter, F. et al. 2004, ApJL 615, 17
Willott, C. J., McLure, R. J., and Jarvis, M. J. 2003 ApJ 587, L15

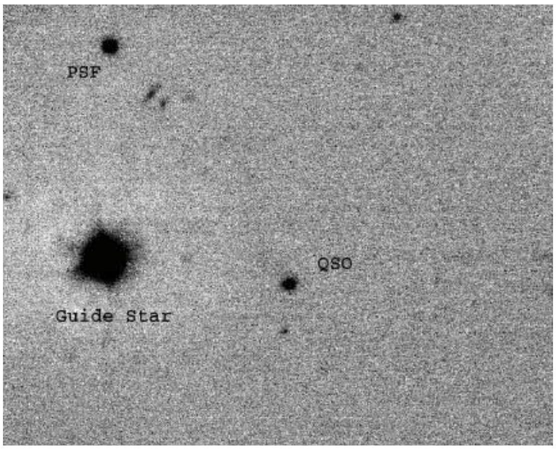

Figure 1: The full NAOS-CONICA field of view of the image of PKS 0113-283 (North is up and East to the left). The guide star used for the adaptive optics and the star used to model the PSF of the system are labeled. The image was obtained in the *K*-band, which at the redshift of the object corresponds to rest *V*-band.

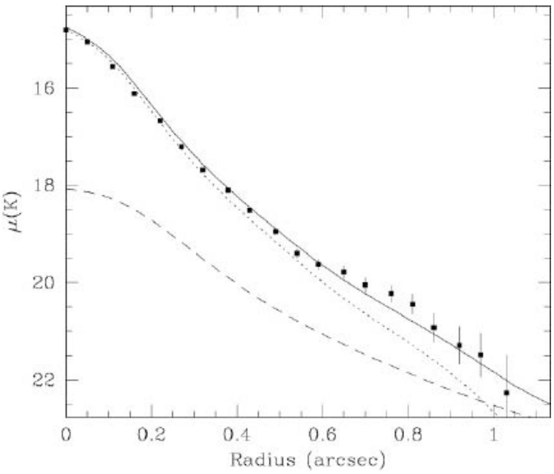

Figure 2: The observed radial surface brightness profiles of PKS 0113-283 (filled squares), superimposed on the fitted model (solid line) consisting of the PSF (dotted line) and an elliptical galaxy convolved with its PSF (dashed line). The associated errors are a combination of the statistical photometry in each bin and of the uncertainty on the background level (that is dominant at the faintest fluxes).

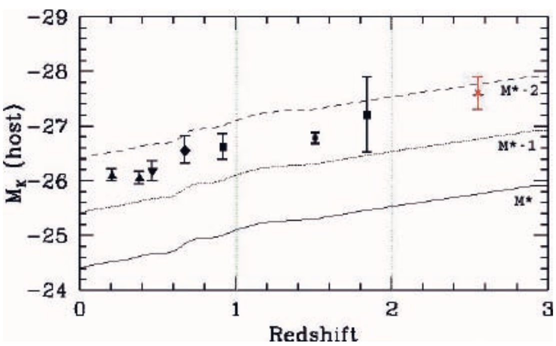

Figure 3: The evolution of radio loud quasar host luminosity compared with that expected for massive elliptical galaxies with magnitude M*, M*-1, and M*-2 (solid, dotted, and dashed line, respectively) undergoing passive stellar evolution. That is, these lines represent the loci of objects with constant mass (constant number of stars), in which stars are getting younger and therefore more luminous as z increases. The new detected host galaxy at $z \sim 2.5$ (in red) is compared with the data for samples of lower-redshift radio-loud quasars (Falomo et al. 2004).