VLT/ISAAC Images of Quasar Hosts at z ~ 1.5

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1. Introduction

Our present knowledge of quasar host galaxies is essentially limited to $z < 1$. Fundamental data come specifically from observations obtained using both Hubble Space Telescope (HST, e.g. Disney et al. 1995; Bahcall et al. 1997; Boyce et al. 1998; McLure et al. 1999) and ground-based 4-m-class telescopes (e.g. McLeod & Rieke 1994, 1995; Taylor et al. 1996; Kotilainen, Falomo & Scarpa 1998; Hutchings et al. 1999; Kotilainen & Falomo 2000; Percival et al. 2000).

Present data indicate that radio-loud quasars (RLQ) are almost exclusively found in galaxies dominated by the bulge (spheroidal) component. These luminous ellipticals exceed by ~ 2–3 mag the typical galaxy luminosity (M^*_H ~ –25; Mobasher, Sharples & Ellis 1993), and are close to the brightest cluster galaxies (M_H ~ –26; Thuan & Puschell 1989). For radio-quiet quasars (RQQ), the situation is less clear, with both types of hosts found.

The characterisation of the properties of the galaxies hosting the most luminous active nuclei is traditionally hindered by the presence of the very bright nucleus that outshines the faint starlight from its host galaxy. Significant improvements for the detection and the study of the surrounding nebulosities have been obtained with the use of CCD detectors on large telescopes and with a "narrow" point spread function (PSF) that greatly helps to increase the contrast of the host light superposed to the nucleus.

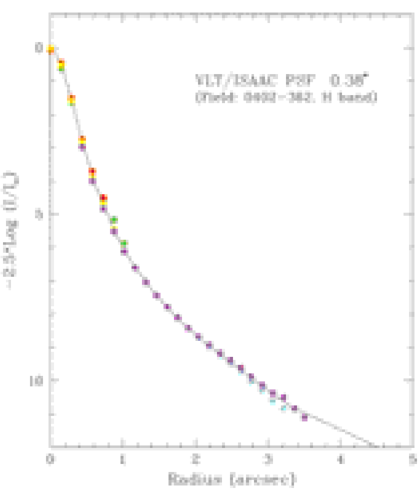

Figure 1: The azimuthal averaged brightness profiles of stars in the field of PKS 0402-362 compared with the PSF model used. The seeing in this frame (UT1+ ISAAC, 1 hour total integration, H filter) is 0.38″.

Moving to high redshift makes the optical light of the nucleus even brighter with respect to the galaxy because of the different intrinsic spectral distributions of host and nucleus while the host galaxy becomes also progressively fainter because of the cosmological dimming of the surface brightness.

In order to cope with these problems, one needs to obtain observations in the NIR with high efficiency and good resolution capabilities. In spite of its superior spatial resolution, HST, with its relatively small throughput with respect to the 8–10-m ground telescopes, may fail to detect faint extended emission with reasonable exposure times. Eight-metre-class telescopes, like the VLT with ISAAC, combine high throughput and (during good seeing conditions) sufficiently narrow PSF to detect and study the underlying nebulosity of quasars. Further improvements are expected to come from the common use of adaptive optics (see e.g. Hutchings et al. 1999) on large telescopes.

In this report we present the results of a pilot study aimed at investigating high z quasar hosts of a sample of radio-loud and radio-quiet quasars with redshift $1.0 < z < 2.0$, and $-25.5 < M_V < -28$. High-resolution images, obtained with the VLT and ISAAC of three RLQs at z ~ 1.5 are shortly discussed (see Falomo, Kotilainen and Treves 2000 for more details). We use $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

2. Observations, Data Analysis, and Results from Individual Objects

NIR *H*-band (1.65 μm) images of the quasars were obtained at Paranal, using ISAAC (Infrared Spectrometer And Array Camera; Moorwood et al. 1998) mounted on the VLT unit telescope ANTU (UT1). The SW arm of ISAAC is equipped with a 1024 × 1024 px Hawaii Rockwell array, with pixel scale 0.″147 px^{-1}, giving a field of view 150 × 150 arcsec (corresponding to ~ 1.8 Mpc at z = 1.5). The observations were performed in service mode during the nights of 20 and 21 October 1999. Each quasar was observed for a total integration time of 1 hour using a jitter procedure and individual exposures of 2 minutes per frame. The jittered observations were controlled by an automatic template (see Cuby 2000), which produced a set of frames slightly offset in telescope position from the starting point. The seeing was excellent during the observations, resulting in stellar FWHM of 0.″50, 0.″41 and 0.″38 in the fields of PKS 0000-177, PKS 0348-120 and PKS 0402-362, respectively.

In order to determine the amount of extended emission around the quasars, one needs to perform a detailed study of the PSF. The relatively large field of view of ISAAC (~ 2.′5) allowed us to perform a reliable characterisation of the PSF. For each field, we analysed the shape of many stellar profiles and constructed a composite PSF, whose brightness profile extends down to μ_H = 24.5 mag $arcsec^{-2}$. This warrants a reliable comparison between the luminosity profile of the quasars and of the stars without requiring extrapolation of the PSF. The shape of the PSF profile was found to be stable across the field of the images (see Figure 1).

For each quasar, we have derived the azimuthally averaged fluxes excluding all regions around the quasars contaminated by companion objects. This procedure yielded the radial luminosity profile out to a radius where the signal became indistinguishable from the background noise (typically μ(H) ~ 24 mag $arcsec^{-2}$, reached at ~ 2″ distance from the nucleus). Modelling of the luminosity profile was then carried out using an iterative least-squares fit to the observed profile, assuming a combination of a point source (PSF) and an elliptical galaxy convolved with the proper PSF.

Absolute magnitudes have been K-corrected (at this z K-corr is < 0.2 mag in H), using the optical-NIR evolutionary synthesis model for elliptical galaxies (Poggianti 1997).

In Figure 2, we show the final images of the three quasars together with their PSF-subtracted images. The PSF scaling factor was adjusted in order to prevent strong negative values in the few central pixels of the residual image. Although this method tends to over-subtract the point source, it gives us a model-independent way to analyse the surrounding nebulosity. After subtraction of the scaled PSF, two out of the three quasar images exhibit clearly extended emission and suggest the presence of knotty structure. For one quasar (PKS 0402-362), only marginal extended emission is detected.

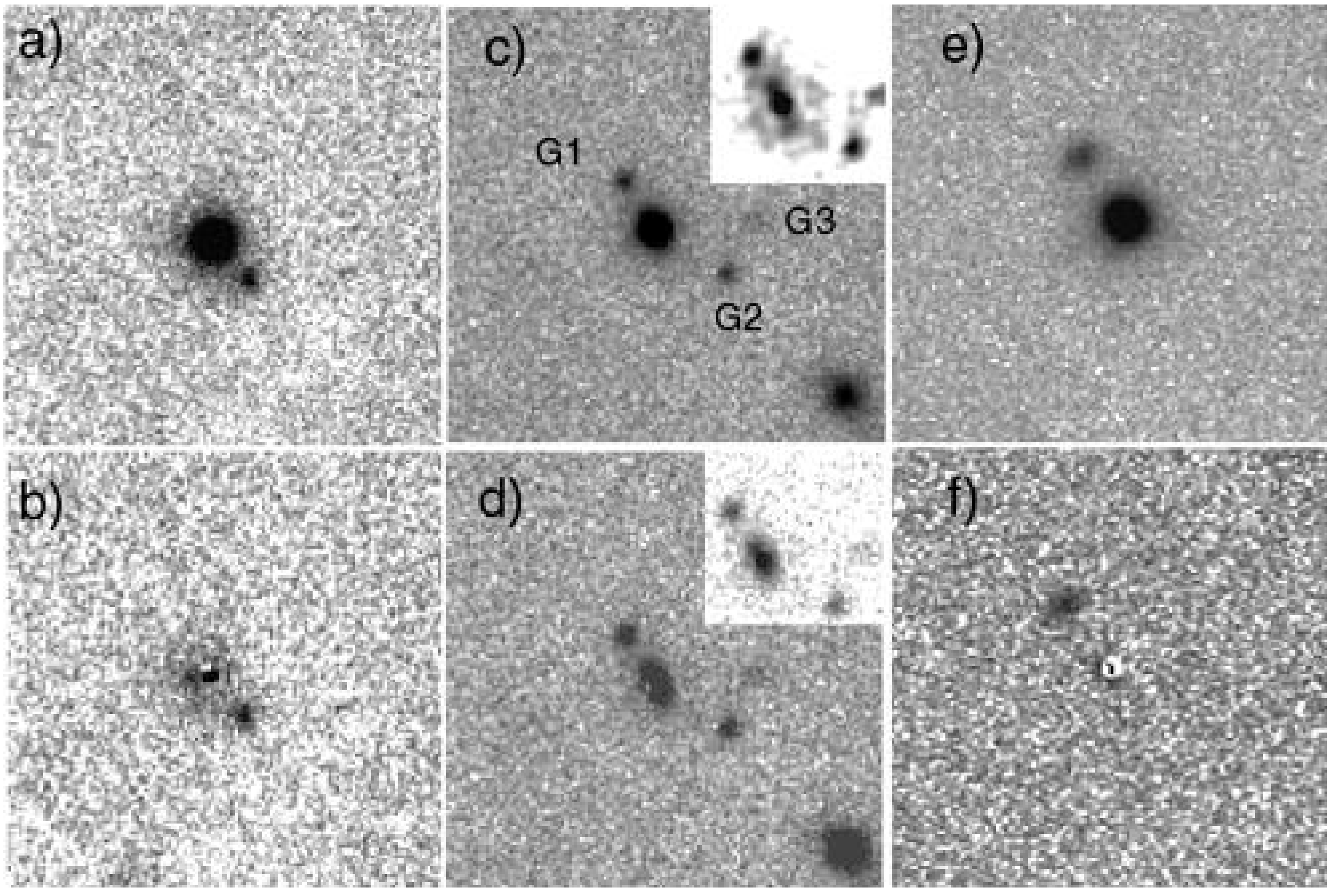

Figure 2: H-band images of the three quasars before (top) and after (below) subtraction of a scaled PSF (see text). From left to right: a), b) PKS 0000-177, c), d) PKS 0348-120 and e), f) PKS 0402-362. The full size of the images in each panel is ~ 17″. North is to the top and east to the left. The inset in panel c) shows the result of a deconvolution of the image. The inset in the panel d) yields a different grey-scale of the central portion of the PSF subtracted image in order to enhance the knot structure.

PKS 0000-177 (z = 1.465) is located at ~ 4″ NW from a m_H ~ 14.5 mag star which, although well separated from the quasar, has been subtracted from the final image to avoid confusion. In our H-band image (Fig. 2a), the QSO appears round and compact with a companion object (m_H = 20.3) at 1.″8 SW. After removing this companion, we note faint "arc-like" structures to the NE and SW at ~ 1.″5 from the nucleus. After subtraction of a scaled PSF at the position of the quasar nucleus (Fig. 2b), some extended nebulosity is clearly detected together with a faint knot at ~ 0.″6 E of the nucleus. After masking the companion, 1.″5 SW of the nucleus, we derived the brightness profile (Fig. 3) that exhibits a significant excess over the PSF, starting at ~ 1″ (12 kpc) radius from the nucleus. Model fit of the profile yields M_H = –27.4 and effective radius R_e ~ 3.5 kpc for the elliptical host. Assuming the redshift of the companion is that of the quasar, the projected distance of the companion galaxy is ~ 21 kpc while its absolute magnitude is M_H = –25.8.

PKS 0348-120 is a flat-spectrum radio quasar at z = 1.520 (Wright et al. 1983). The H-band image of the quasar (Fig. 2c) is clearly extended and elongated approximately along the NE-SW direction. A resolved companion galaxy (G1) with m_H = 20.5 lies at 2.″2 NE from the quasar. The projected distance of this galaxy, if at the redshift of the quasar, is 27 kpc. Other fainter galaxies, G2 and G3 respectively (m_H = 21.1 and m_H = 22.2), are located at 3.″2 (39 kpc) SW, and at 3.″9 (43 kpc) W of the quasar.

From fitting the radial brightness profile (Fig. 3) we obtain a very luminous (M_H = –27.6) and compact (R_e = 4.9 kpc) host galaxy. The profile is not smooth, suggesting the presence of substructures in the host that are revealed in the PSF subtracted image. A knot at 0.″7 (8.6 kpc) from the nucleus along the direction of G1 is visible in Figure 2d. This feature is clearly seen in the deconvolved image of the quasar (see inset in Fig. 2d) using a Lucy-Richardson algorithm implemented in IRAF (Lucy 1991) with 15 iterations.

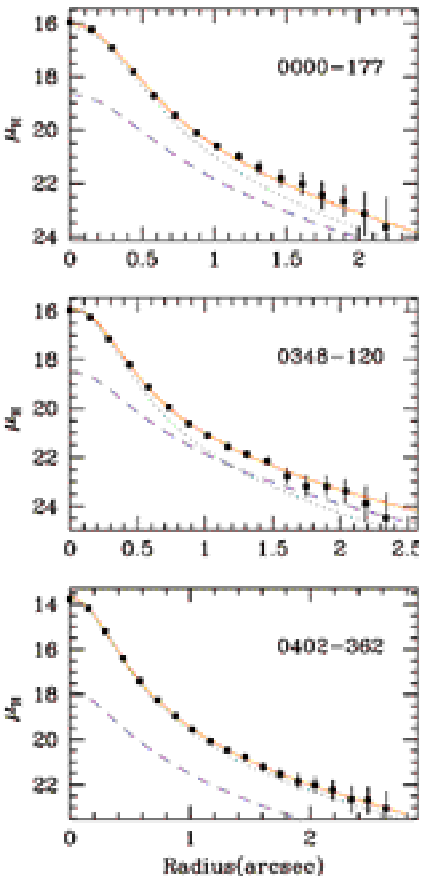

Figure 3: The observed radial brightness profiles in the H band of the three quasars (filled squares), superimposed to the fitted model consisting of the PSF (short-dashed line) and the elliptical galaxy (long-dashed line). The red solid line shows the total model fit.

With the present data, it is not possible to clarify the nature of this circumnuclear emission knot. Most likely, it is another small companion galaxy projected onto the envelope of the quasar host.

PKS 0402-362 is at about the same redshift (z = 1.417) as the other quasars in this study, but the nucleus is ~ 2 mag brighter. The H-band image of this quasar is shown in Figure 2e. The nuclear luminosity is very high, M_H = –30.6, and it out-shines the light from the host galaxy. Using azimuthally averaged radial brightness profile, we substantially improved the signal-to-noise and found a small excess of light over the PSF starting from 1″ distance from the nucleus (Fig. 3). Modelling of this profile suggests a host luminosity of M_H = –27.7 and scale-length R_e ~ 4 kpc. However, since it is small, we consider this only a marginal host detection.

Also in this case we detect a companion galaxy (m_H = 19.5; 2″.8 NE) close to the quasar. Its projected distance is 34 kpc, and if at the redshift of the quasar it would be very luminous (M_H = –26.6; only 1 mag fainter than the quasar host). Note, however, that the optical spectrum of the quasar exhibits a weak absorption system tentatively identified as MgII 2800 Å at z = 0.797 (Surdej & Swings 1981) which, if associated with the companion galaxy, would lead to a reduced M_H = –24.5.

3. Discussion and Conclusions

We have shown that NIR high-resolution imaging obtained with VLT/ISAAC is able to detect extended emission around the active nucleus of distant quasars. These images allow us to characterise the host properties and to investigate their close environment.

The derived NIR host luminosities of these quasars (M_H ~ –27.5) are very bright and correspond to galaxies > 2 mag brighter than M* (M_H = –25; Mobasher et al. 1993). The nuclei are ~ 1.5 mag (~ 3 mag for PKS 0402-362) more luminous than their host galaxies. The scale-length of the hosts ranges from 3 to 5 kpc and appears to be smaller than those observed in low (z < 0.5) and intermediate (0.5 < z < 1) redshift quasar hosts (e.g. McLeod & Rieke 1994; Taylor et al. 1996; McLure et al. 1999; Kotilainen et al. 1998; Kotilainen & Falomo 2000), which typically have scale-lengths of ~ 10 kpc.

The luminosities of the host galaxies of our three RLQs are very similar to those of high-redshift 6C radio galaxies (RG) studied by Eales et al. (1997). In their Hubble diagram, RGs at z ~ 1.5 have K-band magnitude ~ 18.5, while we find < m_K(host) > ~ 18.3 (assuming H–K = 0.2). The similarity with high z RGs is also supported by the knotty structure observed in the hosts of two of the quasars and in the density of the immediate environment (e.g. Best, Longair and Röttgering 1997).

These results underline an evolutionary scenario for RLQ and RG hosts that appears significantly different from that of RQQ hosts. In fact, a recent study of RQQs at z ~ 1.8 and z ~ 2.7, performed with HST and NICMOS in the H-band, was able to resolve 4 out of 5 RQQs (Ridgway et al. 2000). The deduced host luminosities appear 1–2 mag fainter than those found in our RLQ hosts and in the 6C RGs (Eales et al. 1997), and are similar to M*. This suggests that the systematic difference of host luminosity between RLQs and RQQs, already noted at low redshift (e.g. Bahcall et al. 1997 and references therein), is even more significant at higher redshift, indicating a different formation and/or evolutionary history of the two types of AGNs.

Some models of galaxy formation and evolution based on hierarchical clustering (e.g. Kauffmann & Haehnelt 2000) predict progressively less luminous host galaxies for quasars at high redshift. This seems to be in agreement with the observations of high z RQQ hosts (Ridgway et al. 2000; Hutchings 1995), which may still be undergoing major mergers to evolve into the low redshift giant ellipticals but contrasts with our results on high z RLQs and with previous indications that RLQ hosts at z = 2–3 are extremely luminous (Lehnert et al. 1992).

The large-scale environments of the three quasars observed do not appear particularly rich in galaxies with respect to the background. There is no evidence of a rich cluster of galaxies around any of the quasars. However, in all three cases we have detected a companion galaxy of m_H ~ 20±1 at a distance from the quasar < 3″ (40 kpc). Close companion galaxies around quasars have been noted since the first systematic imaging studies of quasars (e.g. Hutchings & Neff 1990; Hutchings 1995; Bahcall et al. 1997; Hutchings et al. 1999) and spectroscopic investigations have shown that, at least in the case of the closest companions, they are often galaxies at the redshift of the quasars (e.g. Heckman et al. 1984; Ellingson et al. 1994; Canalizo & Stockton 1997). These companions are often taken as evidence for interactions with the host and possible trigger of the nuclear activity but their effective role on the QSO phenomenon is far from being understood.

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