The Interplay among Black Holes, Stars and ISM in Galactic Nuclei
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The cosmic evolution of quasar host galaxies

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Abstract. We present near-infrared imaging of the host galaxies of 17 quasars at $1 < z < 2$, obtained with ISAAC at the ESO VLT UT1 under excellent seeing (∼0.4 arcsec). The radio-loud (RLQ) and radio-quiet (RQQ) quasars in the sample have similar distribution of redshift and optical luminosity. Both RLQ and RQQ hosts follow the cosmic evolution of massive inactive ellipticals undergoing passive evolution. This indicates that nuclear activity can occur in all luminous ellipticals without producing a significant change in their global properties and evolution. However, there is a systematic difference by a factor ∼2 in the host luminosity between RLQs and RQQs, which remains the same from z = 2 to z = 0. Quasar hosts are already well formed at z ∼2, in disagreement with hierarchical models of AGN and galaxy formation and evolution models. No correlation is found between the nuclear and the host luminosities. If the host luminosity is proportional to the black hole mass, as in nearby massive spheroids, both types of quasars emit at very different levels with respect to their Eddington luminosity.

1. Introduction

There are nowadays substantial evidence that low redshift ($z \leqslant 0.5$) luminous quasars are hosted by massive galaxies dominated by the spheroidal component (e.g. Dunlop et al. 2003; Pagani et al. 2003 and references therein). This suggests that nuclear activity may be common during the lifetime of a galaxy with recurrent accretion episodes. While radio-loud quasars (RLQ) are exclusively hosted by ellipticals exceeding L* (Mobasher et al. 1993) by ∼2-3 mag, radio-quiet quasars (RQQ) are found both in ellipticals and early type spirals. However, the most luminous RQQs are also hosted mainly in elliptical galaxies (Dunlop et al. 2003). This is consistent with the discovery that nearby massive spheroids host inactive supermassive black holes (BH) (e.g. Ferrarese 2002).

The strong cosmological evolution of quasars (Warren et al. 1994) is similar to the evolution of the star formation history in the Universe (Madau et al. 1998). Therefore, the comparison of the properties of quasar hosts as a function of redshift offers the opportunity to investigate the fundamental link between the formation of massive galaxies and the nuclear activity (Franceschini et al. 1999).

However, at high redshift the characteristics of the quasar hosts are less well defined because of the increasing difficulty to detect a faint nebulosity surrounding a bright nucleus. In fact, the detection of host galaxies at high redshift requires imaging with high spatial resolution and sensitivity, and a well defined PSF for modeling the images. A number of detections of quasar hosts at $z > 1$ have been reported (e.g. Lowenthal et al. 1995; Hutchings 1998; Lehnert et al. 1999; Ridgway et al. 2001; Kukula et al. 2001), but most of these studies are limited by seeing (PSF), image depth, sample size and/or non-homogeneity, and they have failed to provide an unambiguous view of the evolution of quasar hosts and of the differences between RLQ and RQQ hosts. Taking advantage of the excellent PSF and the high throughput of the VLT, we have carried out a program to image the host galaxies of quasars in the redshift range $1 < z < 2$. For full discussion, see Falomo et al. (2004).

2. Sample, observations and analysis

The objects were extracted from the AGN catalogue of Veron-Cetty & Veron (2001), requiring $1.0 < z < 2.0$, $-25.5 < M_B < -28$, and sufficiently bright stars within the field of view to allow a reliable characterization of the PSF. In total, 10 RLQs and 7 RQQs were observed, matched in redshift and optical luminosity distributions. The quasars were imaged in the H- or K-band using the near-infrared (NIR) ISAAC camera (1024^2 px; 0.147 arcsec px^{-1}, field of view $\sim 150^2$ arcsec) on UT1 of VLT at ESO. The seeing was excellent, ranging from $\sim$0.3 arcsec to $\sim$0.6 arcsec (average = 0.4 arcsec). Images were secured using random jitter procedure with exposures of 2 minutes per frame. Data reduction included flat fielding, median sky subtraction and co-addition of aligned frames to produce the final images.

For each field, we analyzed the shape of all stars and constructed a composite PSF profile down to $\mu_K \sim 24.5$ mag $arcsec^{-2}$. For each quasar, we computed the azimuthally averaged radial luminosity profiles, after masking regions contaminated by companions, down to μ(K) $\sim$23–24 mag $arcsec^{-2}$. The luminosity profiles were fitted, using an iterative least-squares fit to the observed profile, into a point source (PSF) and an elliptical galaxy component ($r^{1/4}$ law), convolved with the PSF.

3. Results

3.1. *The evolution of quasar hosts*

For all quasars except one (RQQ HE 0935-1001) the host galaxy is resolved. The average absolute K-band magnitude of the host galaxies is $< M_K >$(host) = –27.55 ± 0.12 and $< M_K >$(host) = –26.83 ± 0.25 for the RLQs and RQQs, respectively. All quasars have host galaxies with luminosity between M^* and M^*-2, where $M^*(K)$ = –25.2 (Mobasher et al. 1993). There is a systematic luminosity difference between RLQ and RQQ host galaxies of a factor $\sim$2 ($\sim$0.7 mag). Similar difference has before been noted for quasars at low redshift (Dunlop et al. 2003) and high redshift (Kukula et al. 2001). As our RLQ and RQQ samples span the same range in redshift and optical luminosity, this result therefore strongly indicates that the difference in host luminosity is intrinsic and remains the same over a wide range of redshift. Fig. 1 (left panel) shows the average luminosities of the host galaxies derived from quasar samples at $z < 2$, either from HST NIR studies, or from NIR ground-based data. Both types of quasars, in spite of their different radio properties, follow the passive evolution of massive ellipticals, with RLQ hosts being a factor of $\sim$2 more luminous than RQQ hosts. Between z = 0 and z = 2 there is no systematic change in this luminosity gap.

Similar cosmic luminosity evolution to that of the quasar hosts is also displayed by radio galaxies (RG) at least out to z $\sim$2.5 (Lacy et al. 2000; Pentericci et al. 2001; Willott et al. 2003). This scenario of a passive evolution of quasar hosts is also consistent with the few spectroscopic studies of low redshift quasar hosts and RGs (e.g. Nolan et al. 2001; de Vries et al. 2000), indicating a dominant old evolved stellar population.

The cosmic evolution traced by quasar hosts up to z $\sim$2 disagrees with semianalytic hierarchical models of AGN and galaxy formation and evolution (e.g. Kauffmann & Hähnelt 2000), which predict fainter (less massive) hosts at high redshift, which merge to form low redshift massive spheroids. Thus, if quasar hosts undergo passive evolution, their mass remains essentially unchanged from z $\sim$2 up to z = 0.

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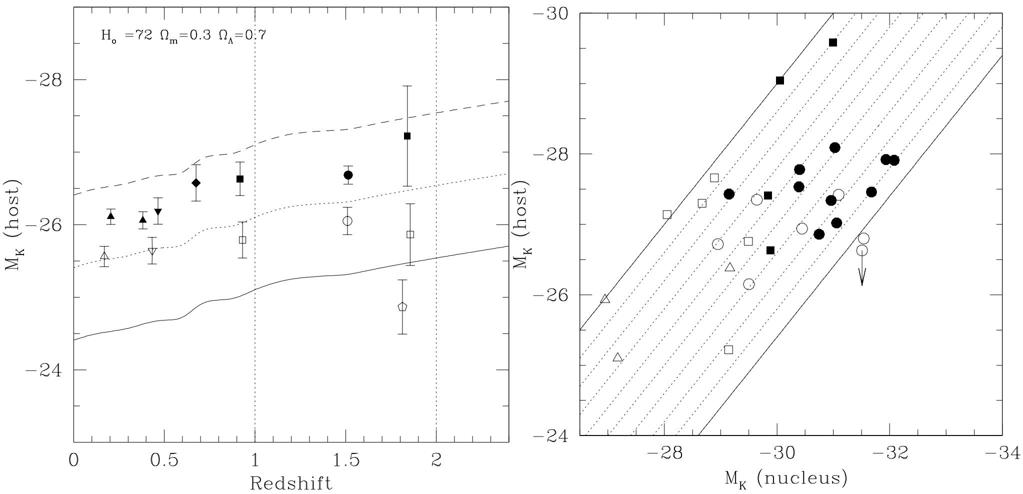

Figure 1. Left: The evolution of quasar host luminosity. Both RLQs (filled symbols) and RQQs (open symbols) follow the passive evolution (Bressan, Granato & Silva 1998) of massive elliptical galaxies (M*, M*-1 and M*-2; *solid,dotted and dashed* line, respectively). Data are from: Pagani et al. 2003 (filled triangles); Dunlop et al. 2003 (open triangle); Hooper et al. 1997 (inverted triangles); Kotilainen et al. 1998 and Kotilainen & Falomo 2000 (diamond); Kukula et al. 2001 (squares); this work (circles); and Ridgway et al. 2001 (pentagon). **Right:** The absolute magnitude of the nucleus compared with that of the host galaxy, for RLQs (filled circles) and RQQs (open circles) of this work, and those from Kukula et al. 2001 (squares) and Ridgway et al. 2001 (triangles). The arrow represents the upper limit for the unresolved RQQ HE 0935-1001. Diagonal lines represent the loci of constant ratio between host and nuclear emission. The two solid lines encompass a spread of 1.5dex in this ratio.

3.2. *Nuclear versus host properties.*

In Fig. 1 (right panel) we compare the K-band host and nuclear luminosities of the quasars. While the host luminosity is distributed over a range of only ∼2 mag, the nuclear luminosities span over ∼4 mag. No significant correlation is found, in agreement with studies of lower redshift quasars (Dunlop et al. 2003; Pagani et al. 2003; but see also e.g. Sanchez et al. 2004 who found correlation for low luminosity AGN). Assuming that the host luminosity is proportional to the BH mass (as observed for nearby massive early type galaxies; Magorrian et al. 1998), and that the nuclear power is proportional to bolometric luminosity (Laor & Draine 1993), the ratio $\eta = L_{nuc}/L_{host}$ is proportional to the Eddington ratio $\xi = L/L_E$. Fig. 1 indicates that high redshift quasars radiate with a wide range of power with respect to their Eddington luminosity ($\Delta\xi \approx$1.5dex). There is no significant difference in $\Delta\xi$ between RLQs and RQQs. Similarly wide spread in ξ was found for low redshift RLQs (Pagani et al. 2003), suggesting that $\Delta\xi$ does not significantly depend on redshift or on radio properties. This is consistent with the evolution of quasars being mainly produced by a density evolution of BH activity due to increased merger and fuelling rate at high redshift (see also Kukula et al. 2001).

4. Open questions

Available samples of reliable quasar host detections at high redshift are still small and do not adequately cover the luminosity–redshift plane. Larger samples covering the full range of nuclear luminosity over a wide redshift interval are required to investigate if and how nuclear luminosity contributes to the luminosity gap between RLQ and RQQ

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hosts (e.g. Floyd et al 2004 found no difference between the host luminosity of RLQs and RQQs at z ∼0.4).

It is important to understand whether the evolution exhibited by quasar hosts is followed by even higher redshift quasars at the peak epoch of quasar activity (z ∼2.5) and beyond. Exploring this issue requires very high sensitivity and very narrow PSF. We have an on-going program to tackle this problem using NIR adaptive optics imaging with NACO on VLT (Falomo et al., in prep.).

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